PB81-120446

Numerical Simulation of Aerated Sludge Composting

(U.S.) Municipal Environmental Research Lab.
Cincinnati, OH

Nov 80

U.S. Department of Commerce
National Technical Information Service
NTIS

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO. EPA-600/2-80-191	2.
3. RECIPIENT'S ACCESSION NO. PB81 120446	
4. TITLE AND SUBTITLE NUMERICAL SIMULATION OF AERATED SLUDGE COMPOSTING	5. REPORT DATE November 1980
	6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) Robert Smith and Richard G. Eilers	8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS Municipal Environmental Research Laboratory--Cin., OH Office of Research and Development U.S. Environmental Protection Agency Cincinnati, Ohio 45268	10. PROGRAM ELEMENT NO. 36B1C
	11. CONTRACT/GRANT NO.
12. SPONSORING AGENCY NAME AND ADDRESS Same as above	13. TYPE OF REPORT AND PERIOD COVERED Inhouse
	14. SPONSORING AGENCY CODE EPA/600/14
15. SUPPLEMENTARY NOTES Contact: Robert Smith (513)684-7624	

16. ABSTRACT

This report describes development of a time-dependent computerized model for composting of wastewater treatment plant sludge with forced aeration of the pile. The work was undertaken because, in the past, development of the composting process for wastewater sludge has been almost wholly experimental and interpretation of experimental results is often difficult without a well organized scientific preception of the phenomena believed to control the process. The model is two-dimensional because piles are long compared to dimensions of the trapezoidal cross-section. The cross-sectional area of the pile is divided into rectangular and triangular areal increments. The pressure source for the forced aeration is along the longitudinal plane of symmetry at ground level. The air flow regime is established first using an iterative solution to LaPlace's equation. Mass flow rates for water vapor, oxygen, and enthalpy are computed around each areal increment. The biological decomposition rate is treated as a function of temperature and moisture content of each areal increment. Finally, properties such as temperature, moisture content, and oxygen concentration are found for each areal increment at each time point. A time interval of 15 minutes was found to give satisfactory results. Physical properties of compost were derived from soil science literature and from limited measurements made by the Los Angeles County Sanitation Districts. Biological properties of compost were taken from work completed for composting of solid wastes. Measurements made on mechanically aerated piles by the Los Angeles County Sanitation Districts were used to test the validity of the model. Computed results agreed reasonably well with measurements but additional research is recommended to maximize the usefulness of the computational approach. The movement of moisture through the pile by capillary action was not included in the model because the necessary measurements needed to characterize the phenomenon are not available.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group

18. DISTRIBUTION STATEMENT Release to public	19. SECURITY CLASS *(This Report)* Unclassified	21. NO. OF PAGES 76
	20. SECURITY CLASS *(This page)* Unclassified	22. PRICE

EPA Form 2220-1 (9-73)

PB81-120446

EPA-600/2-80-191
November 1980

NUMERICAL SIMULATION OF AERATED SLUDGE COMPOSTING

by

Robert Smith

and

Richard G. Eilers

Wastewater Research Division
Municipal Environmental Research Laboratory
Cincinnati, Ohio 45268

MUNICIPAL ENVIRONMENTAL RESEARCH LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
CINCINNATI, OHIO 45268

EPA Form 2350-4 (4-80)
(PREVIOUSLY EIN. EPA FORM 2971)

REPRODUCED BY
NATIONAL TECHNICAL
INFORMATION SERVICE
U.S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA 22161

TYPING GUIDE SHEET

DISCLAIMER

This report has been reviewed by the Municipal Environmental Research Laboratory, U.S. Environmental Protection Agency, and approved for publication. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

FOREWORD

The U.S. Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimonies to the deterioration of our natural environment. The complexity of that environment and the interplay between its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution, and it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems to prevent, treat, and manage wastewater and solid and hazardous waste pollutant discharges from municipal and community sources, to preserve and treat public drinking water supplies, and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research--a most vital communications link between the researcher and the user community.

As the environmental protection movement has grown over the past several years perception of the cost involved in control of pollution has also grown. This has resulted in increasing interest in low cost treatment processes such as composting of wastewater treatment plant sludge. Although experimental research on the process has been substantial engineering analysis has proven to be intractable compared to other wastewater treatment processes. In response to this need this report describes development of a first-generation computerized time-dependent model for the composting process using forced aeration of the pile.

Francis T. Mayo
Director, Municipal Environmental
Research Laboratory

ABSTRACT

This report describes development of a time-dependent computerized model for composting of wastewater treatment plant sludge with forced aeration of the pile. The work was undertaken because, in the past, development of the composting process for wastewater sludge has been almost wholly experimental and interpretation of experimental results is often difficult without a well-organized scientific perception of the phenomena believed to control the process. The model is two-dimensional because piles are long compared to dimensions of the trapezoidal cross-section. The cross-sectional area of the pile is divided into rectangular and triangular areal increments. The pressure source for the forced aeration is along the longitudinal plane of symmetry at ground level. The air flow regime is established first using an iterative solution to LaPlace's equation. Mass flow rates for water vapor, oxygen, and enthalpy are computed around each areal increment. The biological decomposition rate is treated as a function of temperature and moisture content of each areal increment. Finally, properties such as temperature, moisture content, and oxygen concentration are found for each areal increment at each time point. A time interval of 15 minutes was found to give satisfactory results. Physical properties of compost were derived from soil science literature and from limited measurements made by the Los Angeles County Sanitation Districts. Biological properties of compost were taken from work completed for composting of solid wastes. Measurements made on mechanically aerated piles by the Los Angeles County Sanitation Districts were used to test the validity of the model. Computed results agreed reasonably well with measurements but additional research is recommended to maximize the usefulness of the computational approach. The movement of moisture through the pile by capillary action was not included in the model because the necessary measurements needed to characterize the phemonemon are not available.

CONTENTS

Foreword iii

Abstract iv

Figures vi

Tables vii

1. Introduction 1

2. Conclusions and Recommendations 3

3. Description of Compost Model 4

4. Physical Properties of Air and Water 9

5. Physical Properties of Compost 12

6. Air Flow Regime 19

7. Microbiological Heat Generation 22

8. Movement and Storage of Moisture 26

9. Movement and Storage of Heat 29

10. Movement and Consumption of Oxygen 32

11. Comparison of Computed and Measured Results 35

References 43

Appendix 45

FIGURES

Number		Page
1	Discretization scheme for numerical integration of non-aerated composting process	5
2	Discretization scheme for numerical integration of aerated composting process	6
3	Specific volume versus moisture content for Muck soil and compost	13
4	Air flow velocity versus pressure gradient for sludge compost	18
5	Rate of microbiological activity versus compost temperature	23
6	Rate of microbiological activity versus compost solids fraction	25
7	Diagram of LACSD aerated compost pile for wastewater treatment sludge	36
8	Measured and computed interior compost temperatures versus composting time for piles A&B	37
9	Measured and computed interior compost temperatures versus composting time for piles C&D	38
10	PDK and air flow rate (cfm) versus compost solids fraction	41

TABLES

Number		Page
A-1	Input Variables to CMPST	46
A-2	Output Parameters from CMPST	48
A-3	FORTRAN Listing of CMPST	51
A-4	Input Data to CMPST	61
A-5	Printed Output from CMPST	62

INTRODUCTION

Windrow composting of wastewater treatment plant sludge is a promising low cost method for land disposal of sludge. The process consists of mixing dewatered raw or digested sludge with a bulking agent such as previously cured sludge, wood chips, sawdust, or rice hulls and piling the mixture in long (50-150 meters) windrows with a natural trapezoidal cross-sectional shape. The bulking agent is used to increase porosity of the windrow, thus facilitating flow of atmospheric air through the pile for support of aerobic microbiological activity. Aerobic microbiological activity within the windrow pile consumes odor producing organic material with production of heat. The heat destroys pathogenic bacteria and evaporates a portion of the water in the pile to produce a cured compost product which is easily handled and aesthetically acceptable as a soil amendment.

If the porosity provided by the bulking agent is great enough an adequate convective flow of air through the pile can be produced by the temperature difference between pile and atmospheric air. However, forced aeration has been found to be advantageous, especially when raw rather than digested sludge is used. Forced aeration is provided by laying perforated (10 cm dia) air headers under the windrow and using an air blower to draw air through the pile or force air out through the pile. This assures an adequate supply of atmospheric oxygen with a reduction in curing time. Also, if air is drawn into the pile the problem of odor emission is minimized. Since land area needed for the windrows is relatively large (8 mgd/acre) protection from the weather is usually not provided.

Periodic mixing or turning of the windrows is sometimes necessary about once every one to three days to expose all of the sludge to the higher interior temperatures for pathogen destruction and evaporation of water. Turning of the windrows is usually done with a commercially available diesel powered piece of mobile equipment called a composter. Mechanically aerated windrows are usually not turned during the composting period.

Research and development work on windrow composting of wastewater sludge has been primarily empirical in nature. Initial research (1) on composting was conducted by the Agricultural Research Service (ARS), U.S. Department of Agriculture at Beltsville, Maryland. The use of various bulking agents was studied to provide for adequate convective movement of atmospheric oxygen through the windrows. A mixture of three volumes of wood chips to one volume of digested dewatered sludge was found to give good results. Windrows (60 meters long) were laid on a 30 cm layer of wood chips and turned daily for a period of 2-3 weeks. The trapezoidal cross-section of the windrow was 4.5 m wide at the base and 2 m high. Temperature of 55-65^{0} C were achieved at the interior of the windrows and the processed compost was further cured for about 30 days in the storage area. Finally, wood chips were salvaged for reuse by screening.

When the ARS began composting raw dewatered sludge the odor produced by the raw sludge caused complaints from local residents. Forced aeration (2) of the windrow was found to be the best solution to this problem. Perforated air headers (10 cm dia) were laid in the wood chip base and atmospheric air was drawn into the pile and out through the air headers, a water trap, the blower, and finally through a small pile of screened cured compost. Inward flow of air

was maintained for 16-21 days into the composting cycle and then reversed for 8-10 days. The 6 meter wide by 2.5 meter high windrow was also covered with a 30 cm thick layer of screened cured compost. Windrows were not periodically mixed. Temperature and oxygen concentrations at various locations within the windrow were measured (3) over the 28 days composting period. Temperatures reached maximum values of about 75°C and oxygen concentrations a minimum of about 5% at the center of the windrow. Fecal coliform and salmonella bacteria were effectively destroyed.

Over the past several years Los Angeles County Sanitation Districts (LACSD) has conducted extensive research, partially supported by EPA Contract 14-12-15, into both windrow and mechanical composting methods. LACSD has tended to adjust the initial compost porosity by mixing dry cured compost with the dewatered sludge. Portions of the LACSD work were used in development of the model described in this report. In an effort to generalize some of the experimental findings of LACSD, Roger T. Haug developed (4) mass and heat balance relationships for the composting process as a whole. This analysis shows the relationship between available fuel and allowable moisture content in the initial compost mixture to achieve any required moisture content in the cured compost.

Although steady-state mass and heat balance relationships like those developed by Haug are useful for understanding some of the limitations of the process they cannot be used to clarify the essential time-dependent mechanisms which govern the process. This report describes development of a first generation time-dependent simulation model of the windrow composting process with forced aeration.

Most of the mechanisms known to be operative in the process have been included in the model even though reliable measurements for physical and microbiological properties of compost are not available. Many of the properties have been taken from the soil science literature or from other technical disciplines. The finite difference numerical integration scheme used is not the most efficient or the most accurate but it is simple in concept and easily understood by sanitary engineers. The model should be useful as a first step towards establishing a technically sound quantitative research program for overcoming the remaining obstacles preventing widespread use of windrow composting as a sludge disposal method.

In general, current research goals are to avoid odor and particulate emissions from the uncovered compost windrows, to minimize or eliminate the need for wood chips or other inert bulking media used to increase the porosity of the pile, and to reduce the processing time while adequately stabilizing the sludge, destroying pathogenic bacteria, and reducing the water content to a friable level.

CONCLUSIONS AND RECOMMENDATIONS

A first generation, time-dependent, numerical simulation of the aerated composting process for wastewater treatment sludge has been developed and tested against measurements made on the full-sized process. The model is two-dimensional based on the assumption that the length of the trapezoidal cross-section pile is great compared to the dimensions of the cross-section. Measurements made by the Los Angeles County Sanitation Districts research engineers on an obelisk shaped pile 6 meters wide at the base, 2.5 meters high, and 12 meters long were used in validating the model. The performance of four piles operated over a 30 day composting period were used for comparison with computed results. Final solids and volatile fractions agreed reasonably well between computed and measured values. Measurements of interior compost temperature versus time compared less favorably with computed results. The principal problem found in running the simulation program is the tendency of areal increments along the air-compost boundary to become too dry. This problem could be associated with omission of the mechanism for movement of moisture under capillary pressure or with the assumption that water vapor within the pile is always saturated at the local compost temperature. The finite-difference method of numerical integration used appears to be adequate for the simulation. Fundamental measurements of compost physical and microbiological characteristics are needed before the simulation model can be upgraded to a valuable predictive tool. Additional work should be undertaken to adapt the program for simulation of non-aerated compost windrow performance.

DESCRIPTION OF COMPOST MODEL

The trapezoidal cross-sectional area of the compost windrow is divided into a number of rectangular and triangular areal increments one centimeter deep as shown in Figures 1 and 2. If the length of the windrow is great compared to the dimensions of the cross-section the end effects can be neglected and a two-dimensional model is adequate. Also, since the trapezoidal cross-sectional shape is symmetric about the vertical centerline only one-half of the cross-sectional area need be studied. Air enters the aerated pile from a perforated pipe in the longitudinal plane of symmetry at ground level.

The shape of the trapezoidal cross-section is specified by inputting the number (NVB) of vertical blocks, the number (NBB) of blocks along the base of the trapezoid, and the number (NTB) of blocks along the top surface of the trapezoid. For example, in Figure 1; NBV is 10, NBB is 27, and NTB is 7. In Figure 2; NVB is 12, NBB is 29, and NTB is 5. When the width (DX) and height (DY) of the interior blocks are supplied in centimeters as input the dimensions and division scheme for the trapezoidal cross-section are fully determined.

Approximate dimensions of the non-aerated windrow (Figure 1) used by LACSD are 4 ft high, 13 ft wide at the bottom, and 3.5 ft wide at the top. Therefore, by setting DX at 0.475 ft (14.478 cm) and DY at 0.4 ft (12.192 cm) the dimensions of the simulated cross-section are 4 ft high, 12.825 ft wide at the bottom, and 3.325 ft wide at the top. Similarly, dimensions of the aerated pile were 2.5 meters high and 6 meters wide at the bottom with sides sloping at 45^{0}. Thus, if both DX and DY are set equal to 20.83 cm the dimensions of the simulated aerated pile (Figure 2) are 2.5 meters high, and 6.0407 meters wide at the bottom with slides sloping at 45^{0}. Thus, it can be seen that the program has the flexibility to approximate any trapezoidal cross-sectional shape.

Areal increments (blocks) are identified by the row number (I) and the column number (J). For example, the solids fraction of compost in the block in the I'th row and the J'th column is written as FS(I,J). The pressure source which drives ambient air through the pile is always located in the 2'nd row and 2'nd column. Therefore, the number (IV) of the top row of the trapezoid is (NVB+1). Similarly, the number (JB) of the last column on the right will be (NBB+3)/2. and the number (JT) of the first column on the sloping boundary will be (NTB+5)/2. The area (AREA) of the trapezoidal cross-section (excluding the pressure source is computed as follows:

$$AREA = DX*DY(NVB*(NVB+NTB)-1)/2$$

The first phase of computation solves for the horizontal (UX) and vertical (UY) components of air flow velocity at each of the nodal points (black circles) within the windrow cross-section. Flow of air through the compost is assumed to be laminar and obey Darcy's law. An iterative solution of Laplace's equation combining conservation-of-mass and Darcy's law is used. When the blower pressure (PBLOW) is input as a positive value air is forced out through the pile and when PBLOW is negative air is drawn into the pile. Two hundred iterations have been found to be adequate for convergence. The air flow pattern is assumed to persist throughout the composting cycle. A second generation model might adjust the air flow pattern periodically if the relationship between compost physical properties such as moisture content and porosity and the Darcy's law coefficient is known.

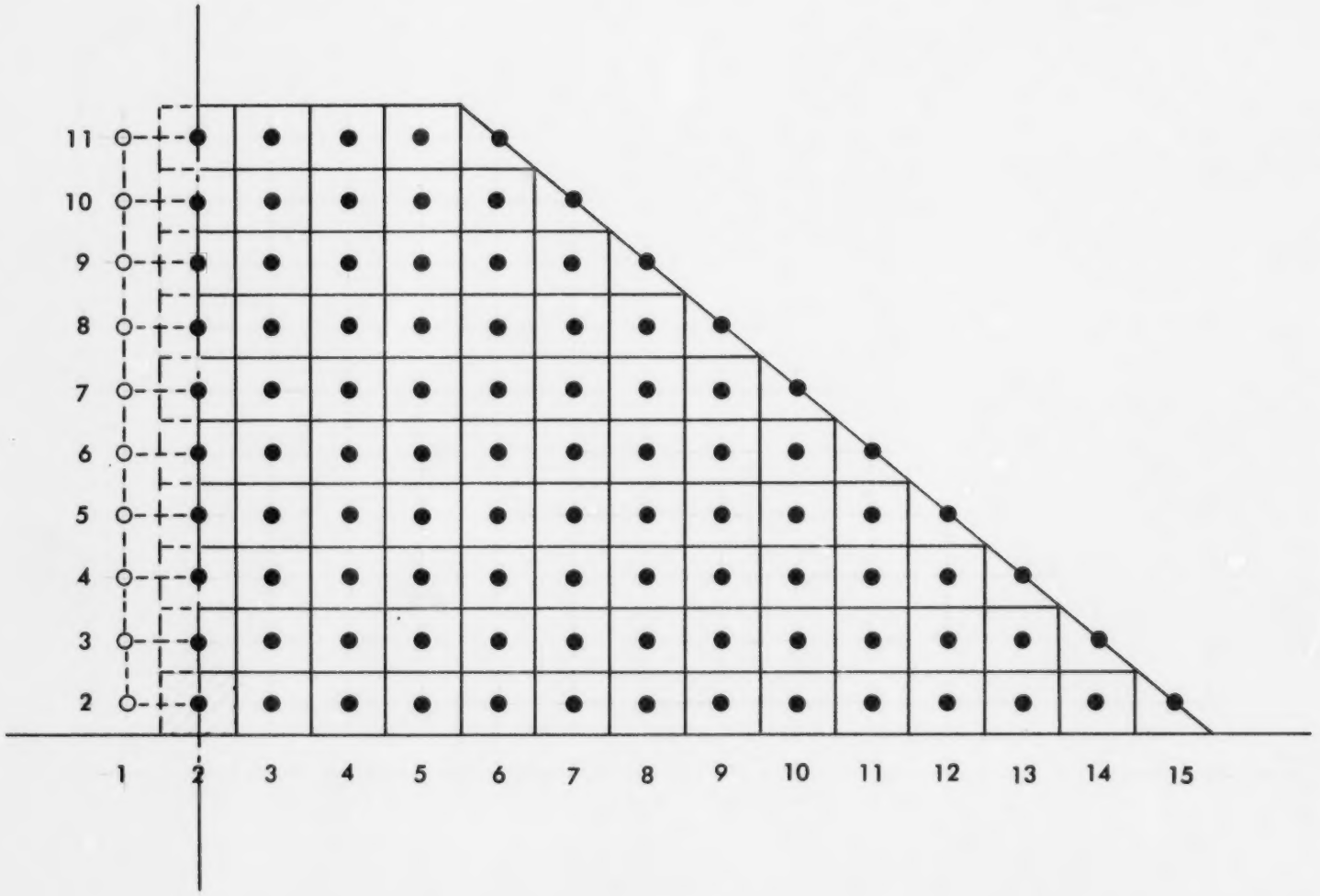


Figure 1. Discretization scheme for numerical integration of non-aerated composting process

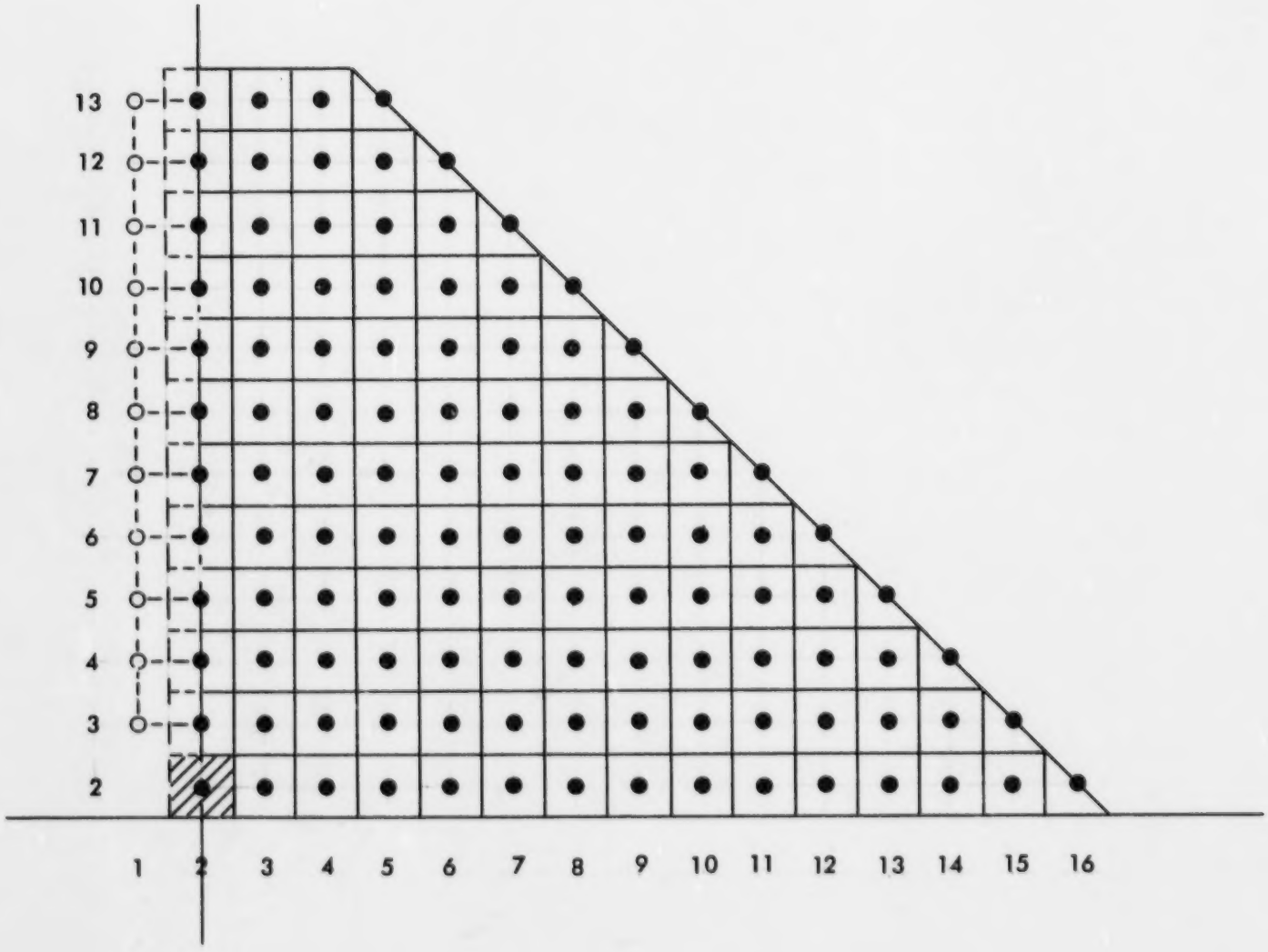


Figure 2. Discretization scheme for numerical integration of aerated composting process

The overall objective of the program (CMPST) is to compute the movement and storage or conversion of water vapor, enthalpy, and oxygen within the pile as a function of time. Time is divided into equal increments (DT) and the number of time increments computed times DT equals the composting period, usually less than 30 days. A time increment of 15 minutes has been found to give good results. At each time point the computation begins by computing the flux of water vapor (gm/hr), enthalpy (cal/hr), and oxygen (gm/hr) into (positive inward) each block. The computation starts with the block in the third row of the second column and proceeds up the second column to the IV'th row. The columns are then considered consecutively from column 3 to column JB always proceeding up the column from the bottom block to the top block. Four flux values are computed for each block. For example, water vapor flux from the left, right, bottom and top are QVL, QVR, QVB, and QVT. Similarly, enthalpy flux values are QHL, QHR, OHB, and QHT and oxygen flux values are QOL, QOR, QOB, and QOT.

Air within the compost pile is assumed to be saturated with water vapor at the local compost temperature. The rate of microbiological heat generation in each block is proportional to the concentration of volatile solids remaining and is also a function of compost temperature and the moisture content. Water is produced as one of the products of combustion; 0.54 gm H_2O per gm of solids combusted. Heat produced is HCOMB cal/gm of volatile solids combusted. Physical properties of compost in the I'th row and J'th column are density (W-(I,J), gm/cc), solids fraction (FS(I,J)), volatile fraction of the solids (FV-(I,J)), and fraction of volatile solids biodegradable (FB(I,J)). The increment of moisture (DH2O, gm/cc) content lost over DT is computed as follows:

$$DH2O = -(QVL+QVR+QVB+QVT)*DT/DA - DVOL*0.54$$

DA = incremental volume, cm^3

DVOL = incremental volatile solids combusted, gm/cc

Relationships used for computing the local microbiological generation of heat (HEAT, (cal/hr)/cc) are given later in this report but DVOL is simply HEAT*DT/HCOMB. Oxygen used (1.6 gm O_2/gm VSS) is also a function of the rate of heat generation. Volumetric heat capacity (VHC, (cal/cc)/^oC) is computed from compost physical properties and the change in compost temperature can then be expressed as follows:

$$T2(I,J) = T1(I,J) + DT*(QHL+QHR+QHB+QHT)/VHC/DA + HEAT*DT/VHC$$

For interior blocks mass transfer of water and oxygen is by advection and diffusion. No mass transfer of water or oxygen is allowed across the soil boundary but loss of water vapor from the boundary with ambient air is computed using a relationship from soil science. Heat transfer within the pile is by conduction and movement of water vapor. Convective heat loss from the boundary with ambient air is computed from heating, ventilating, and air conditioning technology. Heat loss to the soil is computed using anaerobic digester design relationships. Dummy nodes shown by the open circles in column 1 of

Figure 1 are used to provide for symmetry about the vertical centerline in the numerical integration. A running mass balance for water and heat is incorporated in the program as a check on the computations. For example, WOUT is the grams of water lost from the boundary with ambient air and WIN is the water entering the pile with the forced aeration. The difference between WOUT and WIN must equal the water lost (WLOST) from the pile. Similarly, the microbiological heat generated (HUSED) must equal the heat lost from the boundaries with soil and ambient air (HOUT) plus the heat stored in the pile (HSTOR) minus the heat entering with the forced aeration (HIN). The average physical properties of the compost pile are computed at each time point and logic to completely mix the pile at equally spaced time intervals is provided.

PHYSICAL PROPERTIES OF AIR AND WATER

Accurate values for density (gm/cm^3) and enthalpy (gcal/gm) of saturated water vapor can be found in the steam tables (5). However, for ease of computation closed form expressions were derived by fitting the steam table values over the 20-70°C range of interest for compost modeling. The following relationship was found to fit the data over the required range to within about 1%.

$$\text{saturated water vapor density, gm/cc} = e^{5.84726 - 4925.89/T} \quad (1)$$

T = temperature, degrees Kelvin

Steam table values are shown below with estimates made using equation (1):

Temperature, °C	Water vapor density, gm/liter		Percent Error
	True	Estimated	
20	0.01730	0.01730	0.0
30	0.03040	0.03014	-0.86
40	0.05121	0.05066	-1.08
50	0.08313	0.08246	-0.80
60	0.13036	0.13036	0.0
70	0.19833	0.20065	+1.17
80	0.29349	0.30139	+2.70
90	0.42355	0.44267	+4.50

Enthalpy of saturated water vapor above the enthalpy of liquid water at 0°C can be very accurately approximated by the following relationship:

$$\text{saturated water vapor enthalpy, gcal/gm} = 597.44 + 0.4306\ T \quad (2)$$

T = temperature, degrees Celsius

Enthalpy values given in the steam tables are shown below with estimates made using equation (2).

Temperature ^{o}C	Water vapor enthalpy, gcal/gm	
	True	Estimated
0	597.55	597.44
20	606.22	606.05
40	614.83	614.66
60	623.28	623.28
80	631.44	631.89

The error can be seen to be less than 0.1% over the range shown.

According to modern kinetic theory of gases (6) diffusivity of a binary gas mixture is directly proportional to the 1.5 power of the abolute gas temperature and inversely proportional to absolute pressure. The following relationship for diffusivity of water vapor in the air was used by Philip and DeVries (7) in their paper on movement of moisture through porous media.

$$\text{air-water diffusivity, } cm^2/sec = 4.42 \times 10^{-4} \; T^{2.3}/P \qquad (3)$$

T = gas temperature, degrees K

P = absolute pressure, mm Hg

At 25^{o}C the above equation would estimate a value of 0.285 cm^2/sec for air-water diffusivity. Reid and Sherwood (6) reported a measured value at 25^{o}C of 0.260 cm^2/sec. The error incurred in linearizing equation (3) is only about 0.5% over the 20-80^{o}C range. The linearized form expressed as cm^2/hr for use in the program is shown below:

$$\text{air-water diffusivity, } cm^2/hr = 803.0 + 8.81\,T \qquad (4)$$

T = temperature, degrees C

A comparison of diffusivity values found using equations (3) and (4) are shown in the following table.

Temperature, ^{o}C	Philip & DeVries	Linearized Form
20	987.9	979.2
40	1149.9	1155.4
60	1326.0	1331.6
80	1516.3	1507.8

Since the error using the linearized form is a maximum of about 0.5% the linearized form was used in the program.

At zero degrees Celsius, diffusivity of oxygen in air was measured as 0.175 cm^2/sec and oxygen in nitrogen as 0.181 cm^2/sec. according to Reid and Sherwood (6). Thus, if air-oxygen diffusivity is assumed to be directly proportional to the 1.5 power of absolute temperature the following relationship is found:

$$\text{air-oxygen diffusivity, } cm^2/hr = 0.13967\ T^{1.5} \qquad (5)$$

T = gas temperature, degrees K

Within the 20-70°C range equation (5) can be linearized as follows:

$$\text{air-oxygen diffusivity, } cm^2/hr = 625.8 + 3.74\ t \qquad (6)$$

Equation (6) was used in the program.

To calculate the advective flow of enthalpy associated with dry air into each block air density and air enthalpy must both be expressed as a function of air temperature. Using the perfect gas law, air density can be expressed as follows:

$$\text{gas density, gm/cc} = MW/82.05/(T + 273) \qquad (7)$$

Since the molecular weight (MW) of air is usually taken as 28.970 the density of dry air at 20°C can be calculated as 0.001205 gm/cc. Specific heat at constant pressure for air has an average value of 0.2391 gcal/gm per degree Celsius (above 0°C) over the 20-80°C temperature range from the air tables (8). Thus, enthalpy of air can be expressed as 0.2391 T where T is measured in degrees Celsius. Advective flow of enthalpy associated with dry air (gcal/hr) is the product of mass flow and enthalpy per gram. Mass flow is the product of air velocity, air density, and area normal to the velocity. The product of mass flow and unit enthalpy can then be expressed as follows:

$$\text{enthalpy flux, gcal/hr} = (28.97 \times 0.239/82.05)(A \cdot U \cdot T)/(T + 273) \qquad (8)$$

A = area normal to velocity, cm^2

U = air velocity, cm/hr

T = air temperature, °C

The value of the constant in equation (8) is 0.08442

For engineering purposes atmospheric air can be taken as 79% nitrogen and 21% oxygen by volume. Therefore, using a molecular weight of 32 for oxygen in equation (7) and multiplying the result by 0.21 gives an estimate of 0.0002795 gm/cm^3 for the concentration of oxygen in atmospheric air at 20°C.

PHYSICAL PROPERTIES OF COMPOST

From soil science literature it is known that the specific volume (cm^3/gm) of soil is least when the soil is either very wet or very dry and has a maximum value at some intermediate moisture content. This relationship for a muck soil taken from the work of Patten (9) is shown in Figure 3. Measurements of specific volume for wet sludge cake and dry cured compost are given in the March, 1978 progress report (10) from LACSD. Five measurements were made on each material and these are shown by the circled points in Figure 3. Dry cured compost has the greater specific volume. The solid line through the two sets of points can be tentatively taken as the correct relationship between moisture content and specific volume for mixtures of wet sludge cake and dry cured compost. The starting blend of compost used by LACSD ranged from 2 to 3 volumes of dry cured compost per single volume of wet sludge cake. Solids content of the blend can, therefore, be computed as follows where the mixing ratio (R) varies from 2 to 3:

$$FSO = (R*WD*FSD + WW*FSW)/(R*WD + WW) \qquad (9)$$

FSO = solids fraction of blend, fraction

R = volumes of dry compost/volume of wet cake

WD = density of dry cured compost, gm/cm^3

FSD = solids fraction of dry compost, fraction

WW = density of wet cake, gm/cm^3

FSW = solids fraction of wet cake, fraction

Five measurements of solids fraction and volatile fraction of the solids were given in the LACSD progress report (11) for April, 1978. Average values are shown below:

	Solids fraction	Volatile fraction
Wet sludge cake	0.2562	0.4782
Dry cured compost	0.6430	0.3062

Dry solids and moisture mass fractions computed from equation (9) using 2, 2-1/2, and 3 for R are shown below:

R	FSO	1 - FSO
2	0.496	0.504
2-1/2	0.516	0.484
3	0.531	0.469

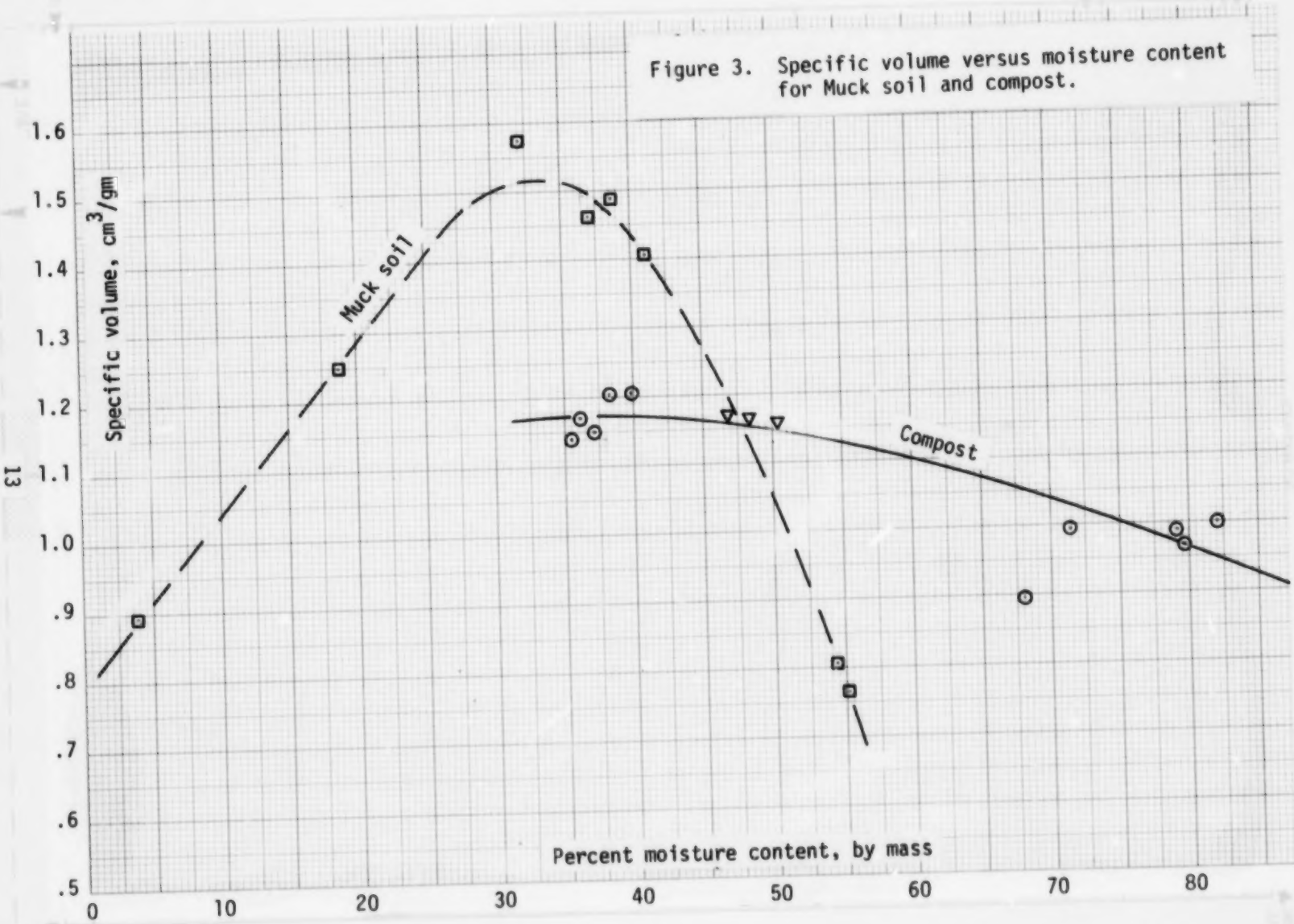


Figure 3. Specific volume versus moisture content for Muck soil and compost.

Expected densities of the starting compost blend can be read from Figure 3 at the points marked by the triangles with the following results:

R	blend density, gm/cm^3
2	0.8711
2-1/2	0.8673
3	0.8621

In the simulation program compost is characterized by the density (W, gm/cm^3), the solids fraction (FS), the moisture fraction (1 - FS), the fraction of solids which are volatile or organic (FV), and the fraction of volatile solids which are biodegradable (FB). Thus, the density (gm/cc) of biodegradable solids can be computed as W*FS*FV*FB. Similarly, the mineral mass fraction is W*FS*(1-FV), the organic mass fraction is W*FS*FV, and the water mass fraction is W*(1-FS). Volume fractions for mineral (XM), organic or volatile (XV), water (XW), and air (XA) can be computed from the density of the mineral, organic, and water components, compost density, and the solids and volatile mass fractions. For soils DeVries (12) gives the following commonly used values for density of the components.

mineral density	2.65 gm/cm^3
organic density	1.30 gm/cm^3
water density	1.0 gm/cm^3
air density	0.00125 gm/cm^3

Using these values for density of the components, the following relationships for computing volume fractions can be derived:

$$XM = FS(1 - FV)W/2.65$$

$$XV = FS\ FV\ W/1.3 \qquad (10)$$

$$XW = W(1 - FS)/1.0$$

$$XA = 1 - XM - XV - XW$$

Using the theory of DeVries (12) for soils the volume fractions computed for compost can now be used to estimate the volumetric heat capacity ($gcal/cm^3/{}^oC$) by means of the following linear relationship:

$$VHC = 0.46\ XM + 0.60\ XV + 1.0\ XW + 0.0003\ XA \qquad (11)$$

VHC = volumetric heat capacity, $gcal/cm^3/{}^oC$

This relationship is used in the program to compute the local volumetric heat capacity of compost. This method of estimation gives values of 0.859 gcal/$cm^3/^oC$ for wet cake, 0.448 for dry cured compost and 0.541 for a 2-1/2 to 1 blend.

Thermal conductivity expresses the capacity of compost to transmit sensible heat and is measured in gm-calories transmitted per square centimeter per hour across a temperature gradient of one degree Celsius per centimeter. An earlier method for synthesizing electrical conductivity of heterogeneous material from measured electrical conductivity of the components was adapted by DeVries (12) to the problem of estimating thermal conductivity of soil. Thermal conductivity measurements for components of soil and compost such as air, water, and mineral and organic substances are available in the literature. Thermal conductivity of air and water are slightly temperature dependent but thermal conductivity of mineral and organic substances are independent of temperature.

The DeVries theory hypothesizes that one of the four components, called the medium will be the principal heat transmitter and treats the other three components as though they are granules suspended in the medium. For compost, water is taken as the medium. If the ratio of the temperature gradient in each suspended component divided by the temperature gradient in the medium (water) is called H (HM for mineral, HV for volatile, and HA for air) the thermal conductivity of compost can be computed as follows:

$$TC = \frac{TW*XW + TM*XM*HM + TV*XV*HV + TA*XA*HA}{XW + XM*TM + TV*XV + TA*XA} \qquad (12)$$

TC = thermal conductivity of compost, mcal/cm/sec/^oC

TW = thermal conductivity of water, mcal/cm/sec/^oC

TV = thermal conductivity of organics, mcal/cm/sec/^oC

TA = thermal conductivity of air, mcal/cm/sec/^oC

TM = thermal conductivity of mineral, mcal/cm/sec/^oC

Values of 7.0 mcal/cm/sec/^oC for mineral material and 0.60 mcal/cm/sec/^oC for volatile organics are given by DeVries (12) as representative. The following relationships were developed from thermal conductivity measurements given by McAdams (13) for air and water.

$$TA = 0.05788 + 0.000182\ T \qquad (13)$$

$$TW = 1.4179 + 0.002219\ T$$

T = temperature, degrees Celsius

In the DeVries theory suspended granules are assumed to be ellipsoidal in shape with three descriptive parameters g_a, g_b and g_c. These three parameters depend on the shape of the granules and their sum must equal one. For example, if granules are assumed to be spherical all three parameters have a value of 1/3. If the granules are assumed to be long circular cross-section rods both g_a and g_b equal 0.5 and the value of g_c is zero.

In computing the thermal conductivity of compost, spherical granules were assumed. The multiplier (H) in the DeVries theory can then be computed as follows:

$$1/HI = 1 + (TI/TW - 1)/3 \qquad (A)$$

HI = HM, HV, and HA

TI = TM, TV, and TA

Using a value of 7.0 mcal/cm/sec/^{o}C for the mineral or non-volatile component of compost, a value of 0.60 mcal/cm/sec/^{o}C for the volatile or organic component and equations (13) for air and water thermal conductivity the following estimates of thermal conductivity for wet cake, dry compost, and the 2.5/1 blend were found:

	20	40	60^{o}C
Wet Cake	1.338	1.374	1.410
2-1/2/1 blend	0.9565	0.9803	1.004
dry compost	0.8894	0.9103	0.9310

Thermal conductivity expressed as mcal/cm/sec/^{o}C

The variation in thermal conductivity over the 20-60^{o}C temperature range is only about 5% while the variation between the starting blend and the dry cured compost is about 7-8%. Because of the obvious weakness of the theory, the volume of computation required, and the relatively small contribution of sensible heat transfer in the mechanics of the process a constant value of 1.0 mcal/cm/sec/^{o}C was used in the simulation of windrow composting. Dividing this value of thermal conductivity by 1000 to convert from mcal to gcal and multiplying by 3600 to convert from sec to hours gives a constant value of 3.6 cal/cm/hr/^{o}C for TC used in the simulation program.

The pressure drop caused by air flowing through porous compost has never been measured carefully. However, a limited series of measurements on a 10 ft cube of compost were reported in the October, 1978 progress report (14) on composting research at LACSD. Although there is some evidence that the pressure drop per unit length versus air flow velocity is non-linear the measurements are too scattered to justify use of a non-linear relationship for fitting the data. Thus, Darcy's law which assumes a linear relationship between air flow

velocity and pressure drop has been used. Darcy's law also provides for the pressure drop to be inversely proportional to viscosity of the air. This refinement has not been included in the simulation but can be added when carefully measured pressure-drop properties of compost are known. The LACSD measurements of pressure drop versus air flow velocity are shown plotted in Figure 4. The simplified form of Darcy's law used to fit the data is shown below:

$$U = PDK(PD/DL) \qquad (15)$$

U = air flow velocity, cm/hr

PD = pressure drop over DL, mbar

DL = incremental distance, cm

PDK = Darcy's Law constant, cm^2/mbar/hr

When measurements of pressure drop versus air flow velocity are available for varying viscosities (air temperatures) PDKO/air viscosity can be substituted for PDK. The value of PDK which fits the straight lines shown in Figure 4 are 39,708 cm^2/mbar/hr for compost with 53% solids and 50,462 for compost with 46% solids. In the simulation program atmospheric air pressure is 1000 mbar at the top of the windrow pile and the pressure maintained at the pressure source at the pile center is -6.14 mbar or 2.5 inches of water (1 mbar = 0.4071 in H_2O).

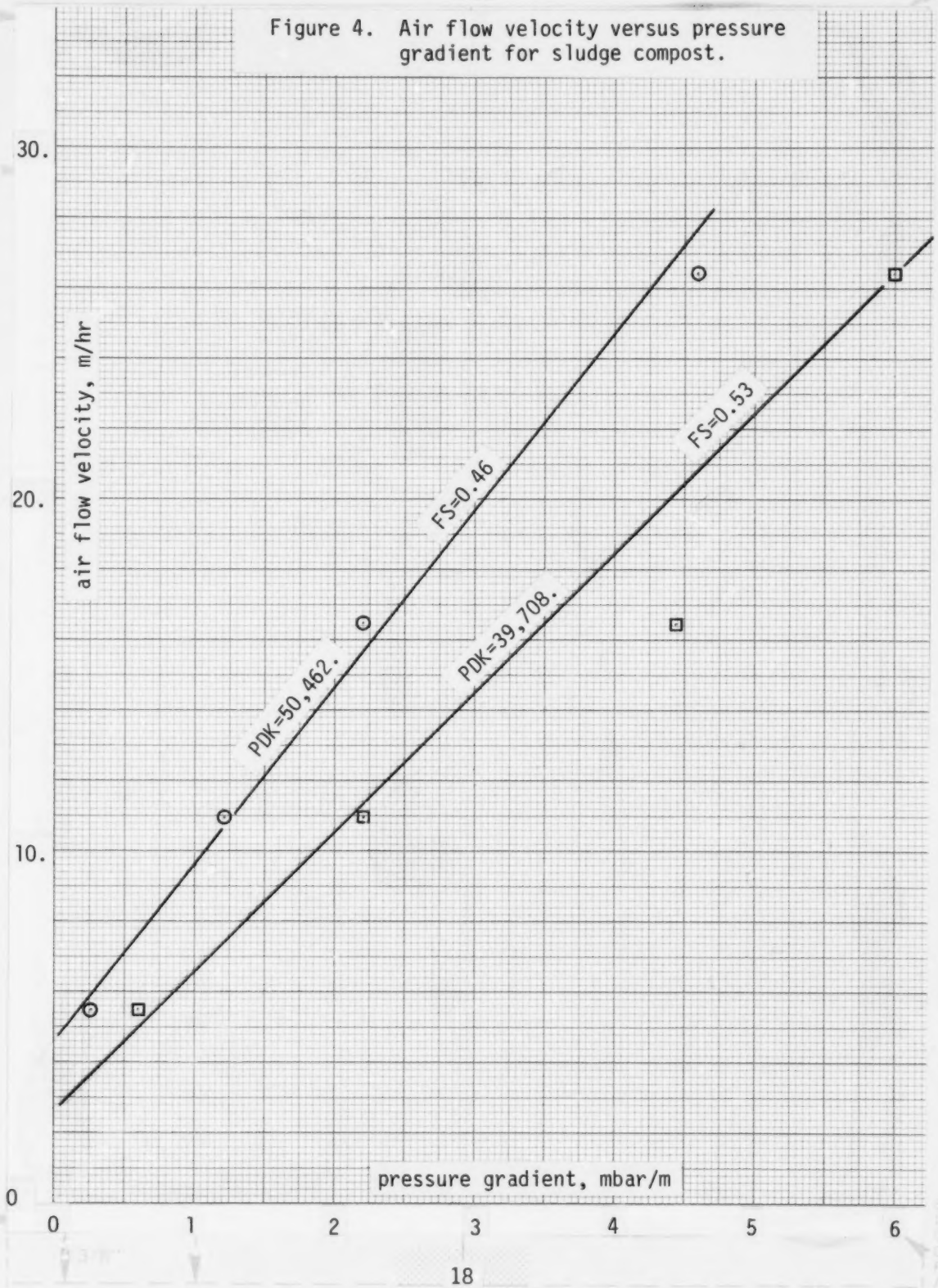


Figure 4. Air flow velocity versus pressure gradient for sludge compost.

AIR FLOW REGIME

Horizontal and vertical components of air flow velocity within the windrow are found by applying Darcy's law and the conservation-of-mass law to each block in the cross-section. Individual blocks or nodes are identified by the row number (I) and the column number (J). Thus, horizontal air flow velocity is UX(I,J) and vertical velocity is UY(I,J). Air flow velocity across any block boundary is associated with the node below or to the left of the boundary. Thus, conservation-of-mass is expressed as follows:

$$DY*(UX(I,J-1) - UX(I,J)) = DX*(UY(I,J) - UY(I-1,J)) \quad (16)$$

Notice that air density has been omitted from the equation. Thus, variations in air density due to temperature differences within the pile are neglected. Air flow velocity across the boundary with the soil is assumed to be zero so for the bottom row of blocks UY(1,J) is set equal to zero.

The computation begins by assigning an initial value for atmospheric pressure at each of the nodal points. Since only pressure differences are used in the computation, atmospheric pressure at the top surface of the windrow is assigned a value of zero. Gravity force causes the initial pressure to increase linearly with distance down from the top surface to the nodal point. Air density (gm/cm^3) is expressed as the molecular weight of air (28.97) divided by the product of the gas constant (82.05) and the air temperature (273 + TAIR) in degrees Kelvin. Multiplying air density by acceleration of gravity (981 cm/sec^2) and noting that 1000 $dynes/cm^2$ equals one mbar gives the following expression for change in atmospheric air pressure with altitude: mbar/cm = 0.3464/(TAIR + 273). Thus, if air temperature is 20°C initial pressure along the second row is 0.001182* DY*(IV - 1.5) mbar. Initial pressure at each of the other rows is assigned in a similar way. In the program the constant 0.3464 is called G.

Darcy's law for flow of air through porous media provides that air flow velocity is directly proportional to the pressure gradient (pressure drop per unit length along the flow path) and inversely proportional to air viscosity. For the initial simulation of windrow composting the effect of viscosity was neglected. Therefore, air flow velocities between nodes can be computed as follows:

$$UX(I,J) = PDK*(P(I,J) - P(I,J+1))/DX \quad (17)$$

$$UY(I,J) = PDK*(P(I,J) - P(I+1)J))/DY - PDK*G/(273 + TAIR) \quad (18)$$

It can be seen that UX is positive to the right and UY is positive when directed upward. Thus, when the pressure source (PBLOW, mbar) is equal to atmospheric pressure at the second row the gradient (P(I,J) - P(I+1,J))/DY equals G/(273 + TAIR) and both horizontal and vertical velocity components are zero at all nodes.

PDK can be evaluated experimentally by pumping air through compost material at a known rate and measuring the pressure drop. Some experiments of this sort using a 10 ft cube of compost were reported in the October, 1978 progress report (14) on composting from LACSD. These data are shown plotted in Figure 4.

It can be seen that the points do not seem to fall on a straight line through the origin as demanded by Darcy's law. This could be due to the measurement technique or the velocity versus pressure drop relationship could be non-linear. An appreciable pressure drop was measured (2.75 in H_2O at 60 cfm) across the empty 10 ft cube used to hold compost material and this was apparently subtracted from the pressure drop across both apparatus and compost to estimate the drop across the compost alone. Details are not given but the data is clearly only a rough estimate of the pressure drop versus flow velocity relationship. The slope of the two lines shown in Figure 4 can be used as a first estimate of PDK.

Pressure existing at steady-state flow conditions can be expressed for all nodes except those in the 2'nd and top row and those along the sloping boundary by substituting equations (17) and (18) into equation (16). In this way the following relationship is found:

$$P(I,J) = CY*(P(I,J+1) + P(I,J-1)) + CX*(P(I+1,J) + P(I-1,J)) \quad (19)$$

$$CY = DY2/(DX2+DY2)/2$$

$$CX = DX2/(DX2+DY2)/2$$

$$DX2 = DX*DX$$

$$DY2 = DY*DY$$

To provide for zero air flow velocity across the soil boundary the following relationship is used to compute the pressure at steady-state conditions instead of equation (19).

$$P(2,J) = (DY2*(P(2,J+1)+P(2,J-1))+DX2*(P(3,J)+DPAIR))/(2.*DY2+DX2) \quad (20)$$

$$DPAIR = DY*G/(TAIR+273)$$

Also, since the steady-state air pressure at the top surface of the pile must be kept at zero and the length of the vertical flow path above nodes in the top row is DY/2 instead of DY the following relationship is used for computing pressure at nodes in the top row except for the single node on the sloping boundary.

$$P(IV,J) = (DY2*(P(IV,J-1)+P(IV,J+1))+DX2*P(IV-1,J))/(2.*DY2+3.*DX2) \quad (21)$$

Equations 19-21 are applied iteratively to all nodes except the nodes on the sloping boundary until the values for pressure converge to the steady-state values. Two hundred iterations have been found to be adequate for achieving convergence.

Air flow velocities between all interior blocks are then computed using equations (17) and (18). Vertical air flow velocities across the upper boundary of blocks in the IV'th row are computed from conservation-of-mass as follows:

$$UY(IV,J) = UY(IV-1,J) - DY*(UX(IV,J) - UX(IV,J-1))/DX \quad (22)$$

Similarly, the vertical and horizontal components of velocity across the sloping boundry of the windrow are computed from conservation-of-mass as follows:

$$UX(I,J) = DY*(DY*UX(I,J-1) + DX*UY(I-1,J))/(DX2 + DY2) \quad (23)$$

$$UY(I,J) = UX(I,J)*DX/DY \quad (24)$$

All velocities are computed as cm/hr and used in the program with these units. However, when printed out they are converted to ft/min. When PBLOW is input as a positive value both vertical and horizontal components of air flow velocity will be positive, that is, directed up and to the right. If, on the other hand, PBLOW is input as a negative value air will flow into the pile from the ambient atmosphere and both vertical and horizontal components of air flow velocity will be negative. The constant K used in mass transfer relationships is set equal to zero when PBLOW is positive and equal to 1 when BPLOW is negative.

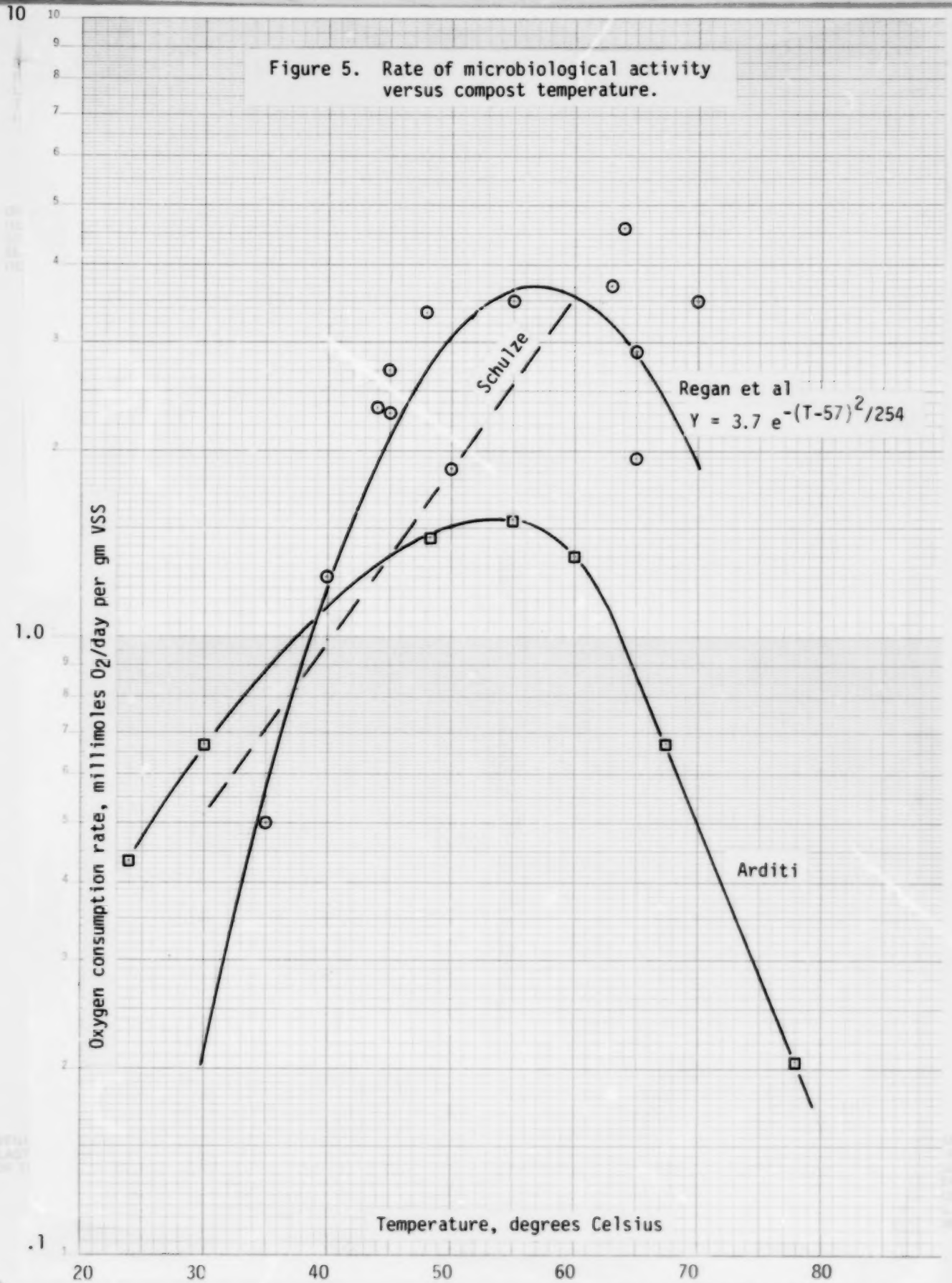
MICROBIOLOGICAL HEAT GENERATION

Aerobic microbiological activity within the compost pile consumes oxygen and volatile solids and produces heat, water vapor, and carbon dioxide. Wiley (15) measured microbiological heat production using municipal refuse in a laboratory composter and reported 10,000-12,000 Btu/lb (5500-6500 cal/gm) of volatile solids destroyed. It will be shown later in this report that if water and volatile solids balances are made on the LACSD results with aerated compost piles these heats of combustion are too low. Therefore, in simulating the LACSD aerated pile performance the high heat of combustion (HCOMB) was set at the value of 9300 cal/gm of volatile solids destroyed given by Wiley for lipids. Oxygen consumed was estimated as 1.6 gm of O_2 per gm of volatile solids destroyed and water produced at 0.54 gm H_2O per gm of volatile solids destroyed.

Rate of microbiological activity is generally agreed to be proportional to the concentration of volatile solids (or biodegradable volatile solids) present. However, compost temperature and moisture content are variables which have a profound effect on the rate of microbiological activity. Jeris and Regan (16) studied the effect of temperature on microbiological activity expressed as millimoles of oxygen used per day per gram of volatile solids present. Activity measurements made by Jeris and Regan on mixed refuse using a laboratory composter are shown by the circled points in Figure 5. Solids fraction of the compost was in the 0.35-0.4 range. It can be seen that the rate peaks at about 57°C and falls off sharply at greater or lesser temperatures. Earlier Schulze (17) investigated composting efficiency within the 35-60°C temperature range and found the log-linear relationship shown by the dashed line in Figure 5.

Measurements by Arditi (18) using a mixture of 50% straw and 50% grass at 55-60% moisture for compost are shown by the squared points in Figure 5. The Arditi data suggest that the effect of temperature is more pronounced at temperatures above the peak than at temperatures below the peak. Andrews (19) used a temperature versus activity relationship of this kind in modeling the thermophilic aerobic digestion process. A temperature versus activity relationship which peaks at 55°C is also reported by Snell (20) but the details of the experiment are not given. The temperature versus oxygen consumption rate relationship is not known for wastewater sludge compost but the shape of the curve is probably similar to those measured for other types of compost. The peak rate probably occurs around 57°C. EMAX used in the program is the peak value for oxygen consumption rate expressed as mmoles O_2/day per gram biodegradable volatile solids. EMIN is the minimum rate found to be necessary at long composting time to prevent the pile temperature from approaching the wet bulb temperature of ambient air rather than the observed 30-40°C range. The form of the relationship used in CMPST is parabolic on semi-log paper which is the same as the normal probability density equation.

Figure 5. Rate of microbiological activity versus compost temperature.



The second important controlling variable on microbiological rate is moisture content of the compost. For mixed refuse the peak microbiological rate occurs at about 30% solids. The rate tends to fall off when the solids fraction is above or below this value. Regan et al (21) made composting rate measurements on mixed refuse over the 50-90% moisture range holding temperature fixed. These data points are shown by the circled points in Figure 6. Schulze (22) also investigated the effect of moisture content on oxygen uptake rate using finished refuse compost at 20°C. The initial refuse was a standardize garbage. A peak rate of 0.567 mmoles O_2 per day per gm of volatile solids was observed at a moisture content of 60.4%. Since the refuse used by Regan et al and Schulze was not the same and the temperature used by Regan et al was not given the Schulze measurements were arbitrarily multiplied by a factor to bring them within the range of the Regan et al data for comparison of the shapes of the two relationships. The adjusted Schulze measurements are shown by the squared points in Figure 6. The relationship between rate and moisture content is not known for wastewater sludge compost so the relationship shown in Figure 6 has tentatively been used in the simulation computer program. The following equation is used in the program for computing oxygen consumption rate:

$$E = EMAX\ e^{-(T-57)^2/254}\quad e^{-10.973(FS-0.3)^2} \qquad (25)$$

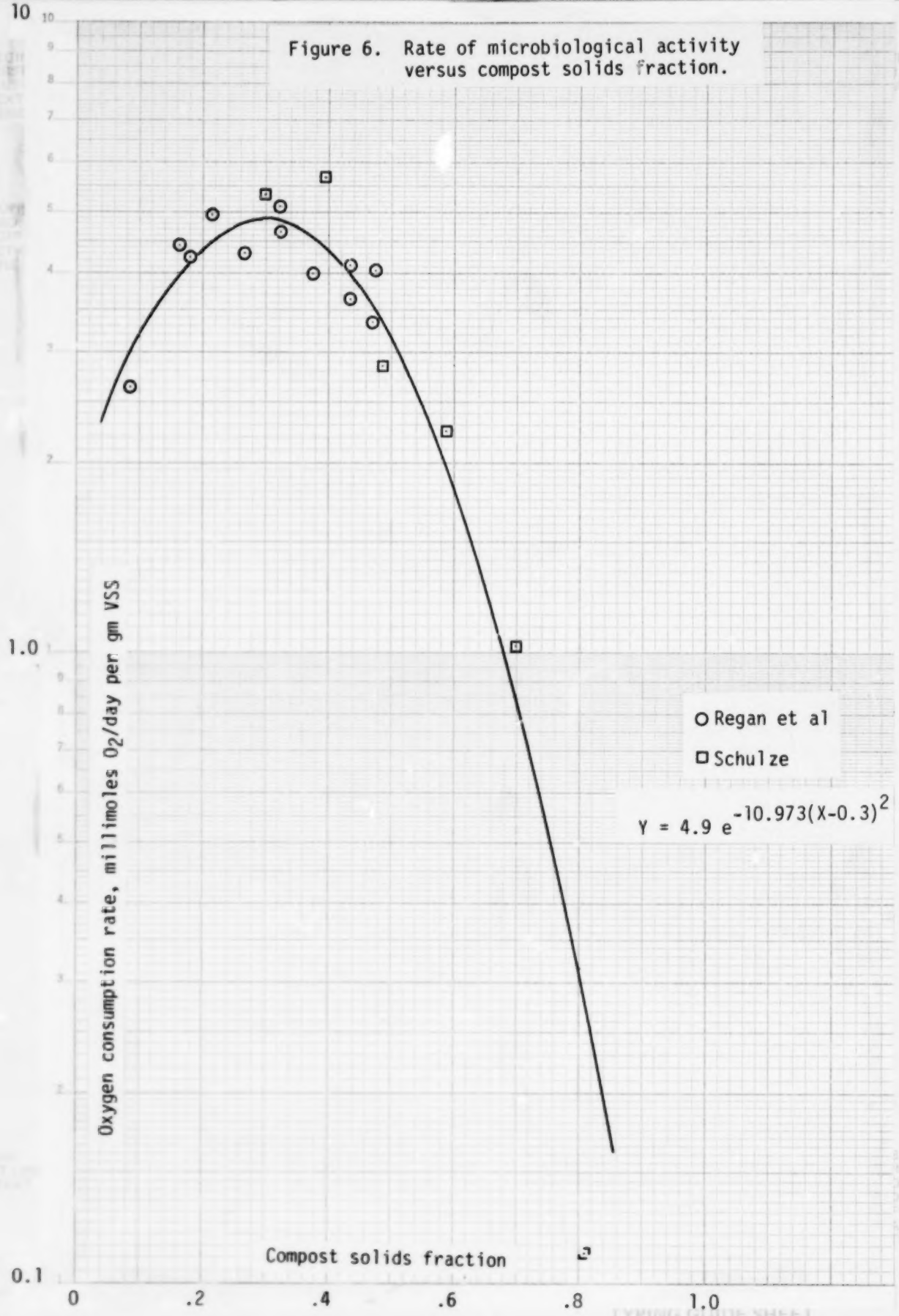
E = oxygen use rate, mmoles O_2/day per gm biodegradable VSS

T = compost temperature, °C

FS = solids fraction

Oxygen consumption rate (E) is converted to grams of volatile solids destroyed per day per gram of biodegradable volatile solids by dividing by 50. This assumes 1.6 grams of oxygen used per gram of volatile solids destroyed. Multiplying the volatile solids use rate by the heat of combustion (HCOMB) and dividing by 24 hr/day gives calories/hr per gram of biodegradable volatile solids present as E*HCOMB/1200. Since the concentration gm/cm^3 of biodegradable volatile solids can be computed as W(I,J)*FS(I,J)*FB(I,J) the heat produced (cal/hr/cm^3) called HEAT in the program is computed as E*HCOMB/1200. *W(I,J)*FS(I,J)*FV(I,J)*FB(I,J). If the value computed for E is less than the input parameter EMIN, E is set equal to EMIN. The program also contains logic to set HEAT equal to zero if the ratio of oxygen concentration in the block divided by ambient oxygen concentration is less than the input value of COMIN. The counter HOFF shows the number of blocks in which E has been set equal to zero in any single DT interval. A value of 0.25 has been used for COMIN.

Figure 6. Rate of microbiological activity versus compost solids fraction.



MOVEMENT AND STORAGE OF MOISTURE

Moisture moves through the aerated compost pile by advection and diffusion and evaporates from the pile surface exposed to atmospheric air. Transfer of moisture across the soil-compost boundary is assumed to be negligible and is set equal to zero in the simulation. Movement of moisture resulting from differing capillary pressures within the compost was not included in the simulation because the required empirical relationships are not available. Capillary action could be an important mechanism in movement of moisture. Water vapor concentration in advective air is assumed to be saturated at the local compost temperature. Four moisture flux rates (gm/hr) are computed for each block at each time point. Flux rates from the left (QVL), right (QVR), bottom (QVB), and top (QVT) are positive when moisture is moving into the block and negative when moving out. For an interior block in the I'th row and J'th column the four flux rates are computed as follows:

```
QVL = DY*(UX(I,J-1)*V(I,J-1+K) + DV*(V(I,J-1) - V(I,J))/DX)

QVR = DY*(-UX(I,J)*V(I,J+K) + DV*(V(I,J+1) - V(I,J))/DX)          (26)

OVB = DX*(UY(I-1,J)*V(I-1+K,J) + DV*(V(I-1,J) - V(I,J))/DY)

QVT = DX*(-UY(I,J)*V(I+K,J) + DV*(V(I+1,J) - V(I,J))/DY)
```

The symbol DV is the product of mean compost porosity (XAM) supplied as input and mean diffusion coefficient for water vapor in air expressed as cm^2/hr. For example, DV used in the equation for QVL is computed as XAM*(803. + 8.81*(T1(I,J) + T1(I,J-1))/2.). In the other three equations DV is computed in the same way except the temperatures used are contiguous to the diffusing surface. K is zero when PBLOW is positive and one when PBLOW is negative.

Moisture entering or leaving the pile advectively is computed crossing the boundaries of block (2,2). A small amount of moisture (0.54 gm H_2O/gm VSS) also enters each block as a result of combustion of volatile solids. Moisture flux across the top boundary of block (2,2) is called WTOP (gm/hr) and moisture flux across the right-hand boundary of block (2,2) is called WRGT. The following equations are used to compute the advective and diffusive flux into or out of block (2,2).

```
  DV = (803. + 8.81*(T1(3,2) + T1(2,2))/2.)*XAM

WTOP = DX/2.*(UY(2,2)*V(2,2) + DV*(V(2,2)-V(3,2))/DY)          (27)

  DV = (803. + 8.81*(T1(2,3) + T1(2,2))/2.)*XAM

WRGT = DY*(UX(2,2)*V(2,2+K) + DV*(V(2,2) - V(3,2))/DX)
```

When PBLOW is positive (K=0) moisture enters the pile through block (2,2) so T1(2,2) is set equal to TAIR and V(2,2) is set equal to VAIR. When PBLOW is positive both WTOP and WRGT will be positive. When PBLOW is negative (K=1) both WTOP and WRGT will be negative and both T1(2,2) and V(2,2) must be computed from WTOP and WRGT values from the last time step. V(2,2) is computed from a water balance written as follows:

$$V(2,2) = (WTOP+WRGT)/(DX/2.*UY(2,2) + DY*UX(2,2)) \quad (28)$$

The enthalpy balance used to compute T1(2,2) is given in the next section of this report. Advective moisture entering or leaving through block (2,2) is summed over the entire composting period and expressed as W22 grams of water computed as follows:

$$W22 = W22 + (WTOP+WRGT)*DT \quad (29)$$

Evaporation of water from a moist surface such as soil has been studied extensively as shown by Taylor and Ashcroft (23) but for rough calculations evaporation of water from a free water surface is often taken as the first approximation. The Meyer relationship given in Chow's Handbook of Applied Hydrology (24) was used in the simulation to estimate evaporation of water from a free water surface. The Meyer equation is expressed as follows:

$$EVAP = CVE*(PW - PA)*(1+WIND/10.) \quad (30)$$

EVAP = evaporation rate, inches water/30 days

CVE = an empirical constant between 11 and 15

PW = saturation vapor pressure for free water, in Hg

PA = water vapor pressure in ambient air, in Hg

WIND = wind velocity in ambient air, miles/hr

Since moisture at the surface of the compost pile is always assumed to be saturated at the compost temperature the known vapor density (gm/cm^3) can be used to compute vapor pressure by assuming water vapor acts like a perfect gas. For example, from the steam tables the ratio of saturated vapor pressure to vapor density ($psi/(lb/ft^3)$) equals $1.071(^oC + 273)$ with little error. Converting to in $Hg/(gm/cm^3)$ the ratio equals $136.64(^oC + 273)$. Since cm of water evaporated is equivalent to gm/cm^2 and 30 days is equivalent to 720 hrs equation (30) can be converted to the following form used in the simulation program.

$$EVAP = 0.482*CVE*DX*(VAIR*(TAIR+273.)-V(I,J)*(T1(I,J)+273.))*(1+WIND/10) \quad (31)$$

EVAP = water evaporation rate, gm/hr

For blocks along the top horizontal boundary with the atmosphere EVAP computed from equation (31) can be added to the advective moisture flux (-UY(I,J)*V(I+K,J)*DX) to compute QVT. For blocks along the sloping boundary with the atmosphere the factor (2.*CX)**0.5 must be included in equation (31) to compute QVT where CX equals DX2/(DX2+DY2)/2. A similar modification is necessary to compute QVR for sloping boundary blocks. A value of 3.0 for CVE has been found to give reasonable agreement with observations.

The change in moisture content (DH2O) and the change in volatile solids content (DVOL) in grams over each time increment are computed where DT is the time increment in hours and DA is the area of the block (cm^2) one centimeter deep. The following relationships are used:

$$DH2O = -(QVL+QVR+QVB+QVT)*DT/DA - DVOL*0.54$$

$$DVOL = HEAT*DT/HCOMB$$

Mass fractions for compost components are then computed at each time point for each of the blocks as follows:

$$FB = (W*FS*FV*FB-DVOL)/(W*FS*FV-DVOL)$$

$$FV = (W*FS*FV-DVOL)/(W*FS-DVOL$$

$$FS = (W*FS-DVOL)/(W-DVOL-DH2O)$$

$$W = W-DVOL-DH2O$$

A running moisture balance around the aerated pile is computed as a check on accuracy of computation. For example, the initial water in the one centimeter slice is computed and added to the total water which would be produced if all biodegradable volatile solids are combusted to find the parameter WPILE. After each DT computation the total moisture in the pile is summed and added to the remaining biodegradable solids times the water to fuel ratio (WRF). This sum is subtracted from WPILE to find the total water lost (WLOST) from the pile at each point in the computation. Water lost from the compost-air boundary is summed over the composting period and called WOUT. The parameter WSTAR is computed as WOUT-W22 and this should equal WLOST for the water balance to be correct. Typical errors are 0.03-0.5% over a 30 day composting period.

MOVEMENT AND STORAGE OF HEAT

Heat (enthalpy) moves within the aerated pile by conduction of sensible heat and by advection of dry air and water vapor. Heat is stored in the pile as sensible heat. Heat moves over the soil boundary by conduction and over the boundary with ambient air by advection, convection, and evaporation of water from the surface. Heat enters the pile through block (2,2) when PBLOW is positive and leaves through block (2,2) when PBLOW is negative.

Conductive heat transfer between blocks is computed as the product of compost thermal conductivity, cross-sectional area normal to flow of heat, and the temperature gradient (^{o}C/cm) normal to the cross-sectional area. Since thermal conductivity of compost (TC) is relatively independent of compost characteristics a mean value of 3.6 cal/hr per cm^2 per unit temperature gradient (^{o}C/cm) was used in the simulation. To estimate conductive heat loss across the soil boundary a method recommended by the ASCE MOP 36 (25) for design of anaerobic digesters was used. In this method the soil temperature gradient is assumed linear extending 10 ft into the soil from the compost surface temperature to the ambient soil temperature (TSOIL) taken as 4.5^{o}C. Soil thermal conductivity was estimated at 16 Btu/hr per square foot per unit temperature gradient (^{o}F/inch) for wet soil and 8.0 for dry soil. The following relationship was used to compute heat flux over the soil boundary with a value of 0.0651 cal/hr per cm^2 per degree Celsius temperature difference for wet soil and one-half the value for dry soil.

```
QHB = HSOIL*(TSOIL-T1(2,J))*DX                                    (32)
```

Heat transfer between interior blocks involves conduction of sensible heat and advection of water vapor and dry air. Air temperature is taken as the local compost temperature and water vapor concentration is taken as the saturation value at the local compost temperature. Enthalpy (cal/gm) of water vapor is approximated as a linear function (597.44 + 0.4306*T) of temperature (T=^{o}C). The previously computed water vapor flux values (QVL, QVR, QVB and QVT) can be multiplied by the enthalpy of water vapor to find the enthalpy flux associated with advection of water vapor. Enthalpy flux associated with advection of dry air is the product of dry air mass flow (gm/hr) and dry air enthalpy (cal/gm). Dry air mass flow is the product of dry air density (gm/cm^3), flow velocity (cm/hr),and cross-sectional area (cm^2). Dry air density is computed as the molecular weight of air (28.97) divided by the gas constant (82.05) and divided by the gas temperature (^{o}K). Dry air enthalpy is taken as 0.2391 times gas temperature in degrees Celsius. Thus, for internal blocks the enthalpy flux from the left, right, bottom, and top into the (I,J) block is computed as follows:

```
QHL = TC*(T1(I,J-1)-T1(I,J))*DY/DX + QVL*(597.44+.4306*T1(I,J-1+K))
      + UX(I,J-1)*.08442*DY*T1(I,J-1+K)/(T1(I,J-1+K)+273.)

QHR = TC(T1(I,J+1)-T1(I,J))*DY/DX + QVR*(597.44+.4306*T1(I,J+K))
      -UX(I,J)*.08442*DY*T1(I,J+K)/(T1(I,J+K)+273.)               (33)
```

```
QHB = TC*(T1(I-1,J)-T1(I,J))*DX/DY + QVV*(597.44+.4306*T1(I-1+K,J))
      + UY(I-1,J)*.08442*DX*T1(I-1+K,J)/(T1(I-1+K,J)+273.)
QHT = TC*(T1(I+1,J)-T1(I,J))*DX/DY + QVT*(597.44+.4306*T1(I+K,J))
      -UY(I,J)*.08442*DX*T1(I+K,J)/(T1(I+K,J)+273.)
```

Heat enters the air-compost boundary by adsorption of solar energy and by advection of air and water vapor when PBLOW is negative. Heat leaves the surface by convection, by evaporation of water from the surface, and by advection when PBLOW is positive. Adsorbed solar energy (SOLAR) is expressed as calories/hr per square centimeter of surface. Solar energy adsorbed at the compost pile boundary has never been measured but measurements (23) of daily average solar energy adsorbed by soil cropped with Bermuda grass in North Carolina ranged from 2-17 cal/hr per cm^2 depending on the month of the year. SOLAR also is known to depend on latitude.

Convective heat loss from the pile surface is estimated in the simulation using the concept of surface conductance (HAIR) from HVAC literature (26). Convective heat loss (cal/hr) is the product of surface area, surface conductance (HAIR), and the temperature difference (^oC) between ambient air and the compost surface. Surface conductance is expressed as a linear function (HAIR=HAIRO+K*WIND) of wind velocity (WIND) in miles/hr. For building materials HAIRO has a value of about 1.0 and K has a value of around 0.15. The empirical equation for estimating evaporation of water from the surface was discussed in the previous section so the moisture flux rate can be multiplied by the enthalpy of water vapor to find the heat flux associated with evaporation of moisture from the surface. Heat flux (QHT, cal/hr) over the boundary of rectangular blocks in the top row is computed as follows:

```
QHT = (HAIR*(TAIR-T1(I,J))+SOLAR)*DX + QVT*(597.44+.4306*T2(I+K,J))
      - UY(I,J)*.08442*DX*T1(I+K,J)/(T1(I+K,J)+273.)          (34)
```

For triangular blocks along the sloping boundary QHT and QHR are computed in a similar way except the factors (2.*CX)**.5 for QHT and (2.*CY)**.5 for QHR must be included in the first term.

Heat also enters the pile through block (2,2) when PBLOW is positive and leaves through block (2,2) when PBLOW is negative. Heat crossing the top boundary of block (2,2) (HTOP) and the right boundary (HRGT) are computed as follows:

$$HTOP = DX/2.*(.08442*UY(2,2)*T1(2+K,2)/(T1(2+K,2)+273.)) + WTOP*(597.44+.4306*T1(2+K,2)) \quad (35)$$

$$HRGT = DY*(.08442*UX(2,2)*T1(2+K,2)/(T1(2+K,2)+273.)) + WRGT*(597.44+.4306*T1(2,2+K))$$

Heat entering or leaving through block (2,2) is summed over the composting period as H22=H22+(HTOP+HRGT)*DT/1000. Thus, H22 is the total heat passing through block (2,2) over the composting time expressed as kilocalories. When PBLOW is positive (K=0) T1(2,2) is set equal to TAIR. However, when PBLOW is negative T1(2,2) must be computed from an enthalpy balance using the parameters from the previous time period. The following equations are used:

$$TEMP = (T1(3,2)+T1(2,3))/2. + 273. \quad (36)$$

$$A = HTOP+HRGT-(WTOP+WRGT)*597.44$$

$$B = .4306*(WTOP+WRGT)+.08442*(DX/2.*UY(2,2)+DY*UX(2,2))/TEMP$$

$$T1(2,2) = A/B$$

Heat is generated within each block by microbiological activity and the compost temperature in each block at the end of any time increment (DT) is computed as follows where T2 is the temperature (^{o}C) at the end of the time increment and T1 is the initial temperature.

$$T2 = T1 + DT*(QHL+QHR+QHB+QHT)/VHC/DA + HEAT*DT/VHC$$

A check on the accuracy of the computations is provided by a running enthalpy balance around the one centimeter thick slice of compost. The total heat of combustion of all fuel (biodegradable volatile solids) within the slice is computed initially and at each time point along the composting period. Heat produced by combustion up to any time point is computed using HCOMB and the remaining mass of biodegradable volatile solids and called HUSED in kcal. Total heat crossing the boundaries with air and soil (positive out, negative in) is summed and printed out at each time point as HOUT in kcal. Sensible heat stored in the compost is computed and called HSTOR as kcal. Heat entering or leaving through block (2,2) is summed (positive in, negative out) and called H22 in kcal. The enthalpy balance then requires that HUSED = HOUT + HSTOR - H22. The terms on the right of this equation are summed and printed out as HSTAR. The typical error between HUSED and HSTAR is in the range of 0.2-0.6% over a 30 day composting period.

MOVEMENT AND CONSUMPTION OF OXYGEN

Atmospheric oxygen moves through the pile by advection and diffusion and is consumed within the pile as a result of microbiological destruction of volatile solids. Volume or mole fractions for the two principal components of air are taken as 0.21 for oxygen and 0.79 for nitrogen. The perfect gas law is then used to compute the density (gm/cm^3) of oxygen in ambient air as 0.0819/(273.+TAIR). The diffusion coefficient for oxygen in air has been measured (6) as 0.175 cm^2/sec. at zero degrees Celsius. Since theory predicts that the diffusion coefficient will increase with temperature directly proportional to the 3/2 power of absolute gas temperature, the following linear relationship can be used to approximate the diffusion coefficient over the 20-75^oC interval.

$$\text{Diffusion Coefficient, } cm^2/hr = 625.8 + 3.74*T \qquad (37)$$

$$T = \text{gas temperature, } {}^oC$$

An average value for porosity (XAM) is used and the temperature used to compute the diffusion coefficient (DO) is the average temperature of the two contiguous blocks between which diffusive mass transfer occurs. When the diffusion coefficient is expressed in this way the flux of oxygen (gm/hr) entering each block from the left, right, bottom, and top is computed as follows for internal blocks:

$$QOL = DY*(UX(I,J-1)*CO1(I,J-1+K) + DO*(CO1(I,J-1)-CO1(I,J))/DX)$$

$$QOR = DY*(-UX(I,J)*CO1(I,J+K) + DO*(CO1(I,J+1)-CO1(I,J))/DX) \qquad (38)$$

$$QOB = DX*(UY(I-1,J)*CO1(I-1+K,J) + DO*(CO1(I-1,J)-CO1(I,J))/DY)$$

$$QOT = DX*(-UY(I,J)*CO1(I+K,J) + DO*(CO1(I+1,J)-CO1(I,J))/DY)$$

The constant K has a value of zero when PBLOW is positive and a value of 1.0 when BLOW is negative.

The approach used in computing the change in oxygen concentration within each block over the time interval DT is to treat the block as a stirred vessel with a constant oxygen flux entering and a flux out of the block directly proportional to the concentration of oxygen within the block. Thus, if the oxygen concentration within the block is C (gm/cm^3), volume of the block is DA (cm^3), flux entering the block is QOIN (gm/hr), rate of oxygen used in biological activity is QOH (gm/hr) and volume of air leaving is QOUT (cm^3/hr) the following differential equation can be integrated over the time interval DT.

$$DA(dC/dt) = QOIN - QOH - C(QOUT) \qquad (39)$$

Equations (38) for the flux rates into each internal block can be divided into flux into the block and flux out of the block by first defining the following terms with the dimensions of cm^3/hr.

$$DOL = DY*(625.8 + 3.74*(T1(I,J) + T1(I,J-1))/2*XAM/DX$$

$$DOR = DY*(625.8 + 3.74*(T1(I,J) + T1(I,J+1))/2)*XAM/DX*RBF \quad (40)$$

$$DOB = DX*(625.8 + 3.74*(T1(I,J) + T1(I-1,J))/2)*XAM/DY$$

$$DOT = DX*(625.8 + 3.74*(T1(I,J) + T1(I+1,J))/2)*XAM/DY*TBF$$

Oxygen flux due to biological activity is independent of the direction of air flow and can be calculated simply as QOH = HEAT*DA*1.6/HCOMB assuming 1.6 gm O_2 used per gm solids combusted. The diffusive inward flux is also indepdendent of air flow direction and can be written as follows:

$$QDOIN, gm/hr = DOL*CO1(I,J-1) + DOR*CO1(I,J+1) \quad (41)$$

$$+ DOB*CO1(I-1,J) + DOT*CO1(I+1,J)$$

Similarly, outward diffusive flux is proportional to C and is written simply as C*(DOL+DOR+DOB+DOT). When the flow of air is outward (K=0) the inward flux of oxygen is therefore expressed as follows:

$$QOIN = DY*UX(I,J-1)*CO1(I,J-1) + DX*UY(I-1,J)*CO1(I-1,J) + QDOIN$$

When the flow of air is outward (K=1) QOIN is computed as follows:

$$QOIN = QDOIN - DY*UX(I,J)*CO1(I,J+1) - DX*UY(I,J)*CO1(I+1,J) \quad (42)$$

The term QOUT is defined as follows when the flow of air is outward (K=0).

$$QOUT = DY*UX(I,J) + DX*UY(I,J) + DOL + DOR + DOB + DOL \quad (43)$$

When the flow of air is inward (K=1) QOUT is computed as follows:

$$QOUT = DOL + DOR + DOB + DOT - DY*UX(I,J-1) - DX*UY(I-1,J) \quad (44)$$

When the parameter A is defined as (QOIN-QOH)/DA and a second parameter B is defined as QOUT/DA equation (39) can be expressed as dC/dt = A - B*C and integrated over the time interval DT with the following result:

$$CO2(I,J) = A*(1 - 1./EXP(B*DT))/B + CO1(I,J)/EXP(B*DT) \quad (45)$$

This relationship is used to compute the oxygen concentration at the end of the time period DT from the concentration at the beginning of the time period and the oxygen flux values for each internal block.

Some modifications are necessary for the boundary blocks in the IV'th row and along the sloping boundary. For blocks in the top row the only modification necessary is substituting DY/2 for the diffusing distance instead of DY. This is done by assigning a value of 2.0 to the parameter TBF and a value of 1.0 to RBF. For blocks along the sloping boundary the diffusing distance is taken as the distance from the surface to the centroid computed as (DX2*DY2/3)/(DX2+DY2)**0.5 and the surface area normal to the diffusion flux is (DX2+DY2)**0.5. Using these

expressions for the diffusing distance and normal area the sum of diffusive mass transfer rates across the boundary; QDOT vertical and QDOR horizontal can be computed as follows:

$$QDOT + QDOR = DO*(DX/DY + DY/DX)*(COAIR - CO1(I,J))*3. \quad (46)$$

However the sum of the diffusive portions of QOR and QOT can be taken from equation (38) and written as follows:

$$QDOT + QDOR = DO*(DX/DY + DY/DX)*(COAIR - CO1(I,J)) \quad (47)$$

Since these expressions, equations (46) and (47), differ only by a factor of 3 equations (40) can be used for the sloping boundary provided both RBF and TBF are assigned a value of 3. Logic is provided in the simulation program to assign a value of 2 to TBF or a value of 3 to both TBF and RBF depending on whether the boundary block is on the top row or on the sloping boundary.

COMPARISON OF COMPUTED AND MEASURED RESULTS

In June, 1978 LACSD research engineers constructed four obelisk shaped aerated compost piles and measured the internal temperature over the 30 day composting period. A diagram of the piles which were 2.5 meters high, 6.0 meters wide at the base and 12 meters long is shown in Figure 7. Measurements of average internal compost temperature reported in the July, 1978 LACSD progress report (27) are shown in Figure 8 for piles A&B and in Figure 9 for piles C&D. Temperature measurements were made along the vertical plane of symmetry at a depth of one-half the pile height. Five separate measurements were made and averaged; three near the center of the pile and one on each end of the pile. In the simulation the measured temperature was computed as TAVG = (T2(7,2)+T2(8,2))/2.

In the experiments, atmospheric air was drawn continuously into all four piles except for the last 9-10 days of the composting periods of piles A&D when the air flow direction was reversed in the hope of promoting drying. Air flow rate through the piles was set at a nominal rate of one cubic foot per minute per cubic yard of compost in the pile. Neglecting end effects this is equivalent to 2.22 cm^3/hr per cubic centimeter of compost. The pressure drop across the pile was measured as 2.5 inches of water or 6.14 mbar and this value was used in the simulation. The ratio (PDK) of air flow velocity to pressure gradient (mbar/cm) decreases as solids fraction (FS) increases so that the volume of air drawn through the piles probably decreased throughout the composting period.

Average solids fraction and volatile fraction was measured for all four piles initially and at the end of the composting period. These reported measurements are shown in the following table.

	Start	End
Pile A	FSI = 0.573 FVI = 0.299	FSE = 0.723 FVE = 0.281
Pile B	FSI = 0.574 FVI = 0.309	FSE = 0.686 FVE = 0.271
Pile C	FSI = 0.515 FVI = 0.328	FSE = 0.653 FVE = 0.318
Pile D	FSI = 0.522 FVI = 0.322	FSE = 0.653 FVE = 0.300

In the table FSI and FVI are the initial solids and volatile fractions and FSE and FVE are the solids and volatile fractions at the end of the composting period. Since non-volatile solids will be unaffected by the composting process a mass balance for non-volatile solids will show the ratio (R) of pile mass before and after composting. Let VI and WI equal the initial pile volume (VI, cm^3) and initial pile density (WI, gm/cm^3) while VE and WE are the corresponding values at the end of the composting period. A mass balance for non-volatile solids is written as follows:

$$VI*WI*FSI*(1-FVI) = VE*WE*FSE*(1-FVE)) \quad (48)$$

$$R = (VI*WI)/(VE*WE) = (FSE*(1-FVE))/(FSI*(1-FVI))$$

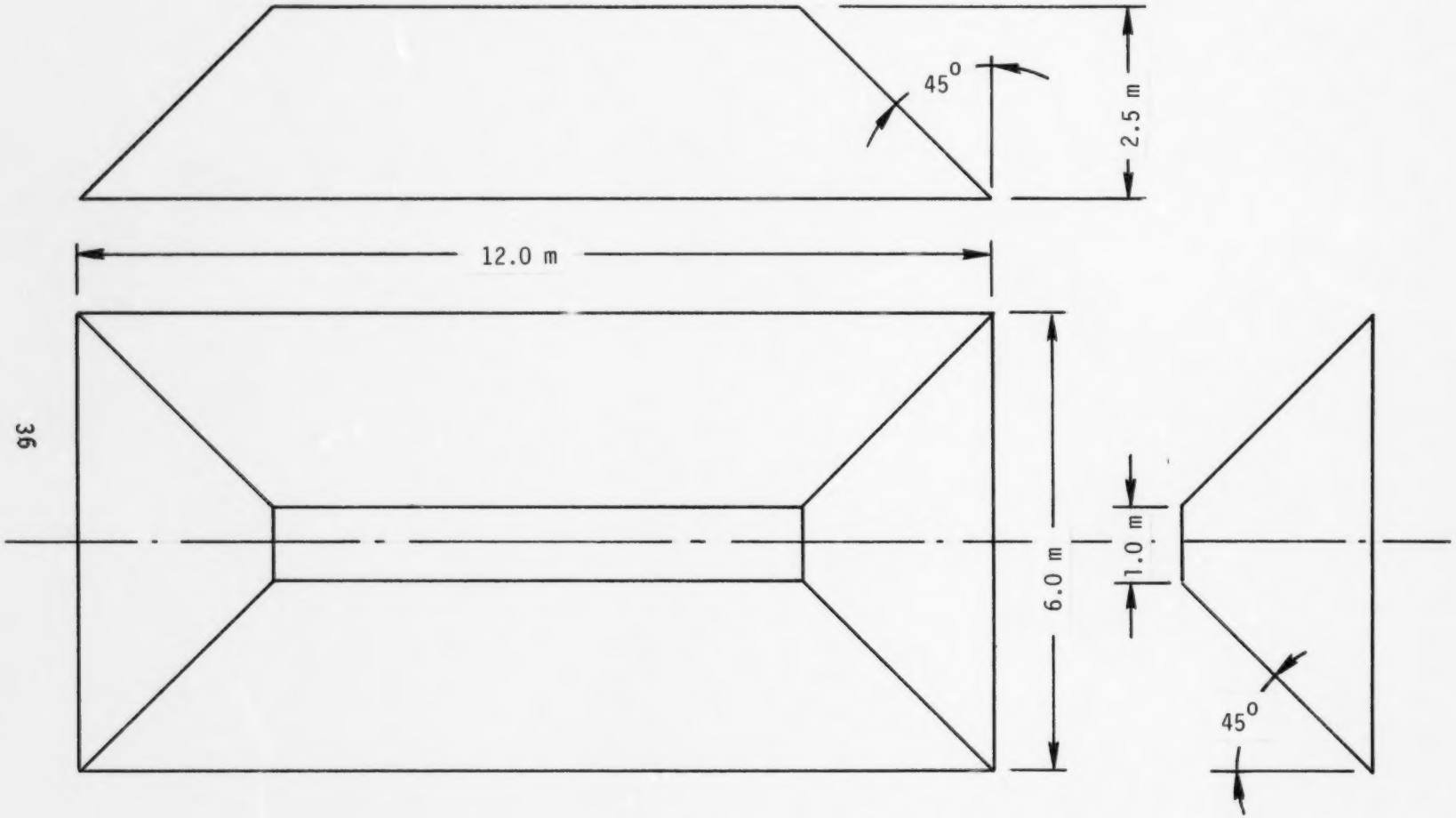


Figure 7. Diagram of LACSD aerated compost pile for wastewater treatment sludge.

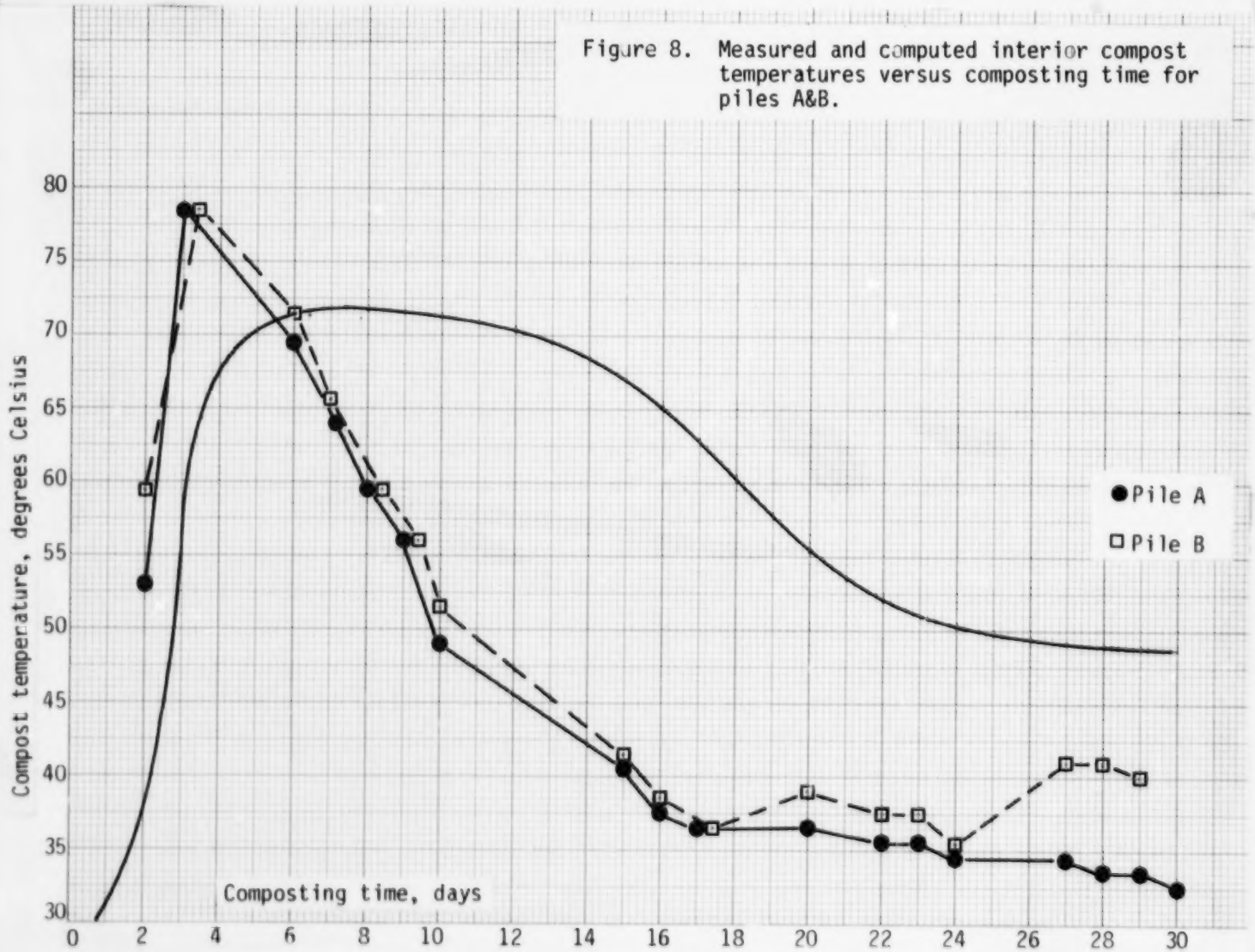


Figure 8. Measured and computed interior compost temperatures versus composting time for piles A&B.

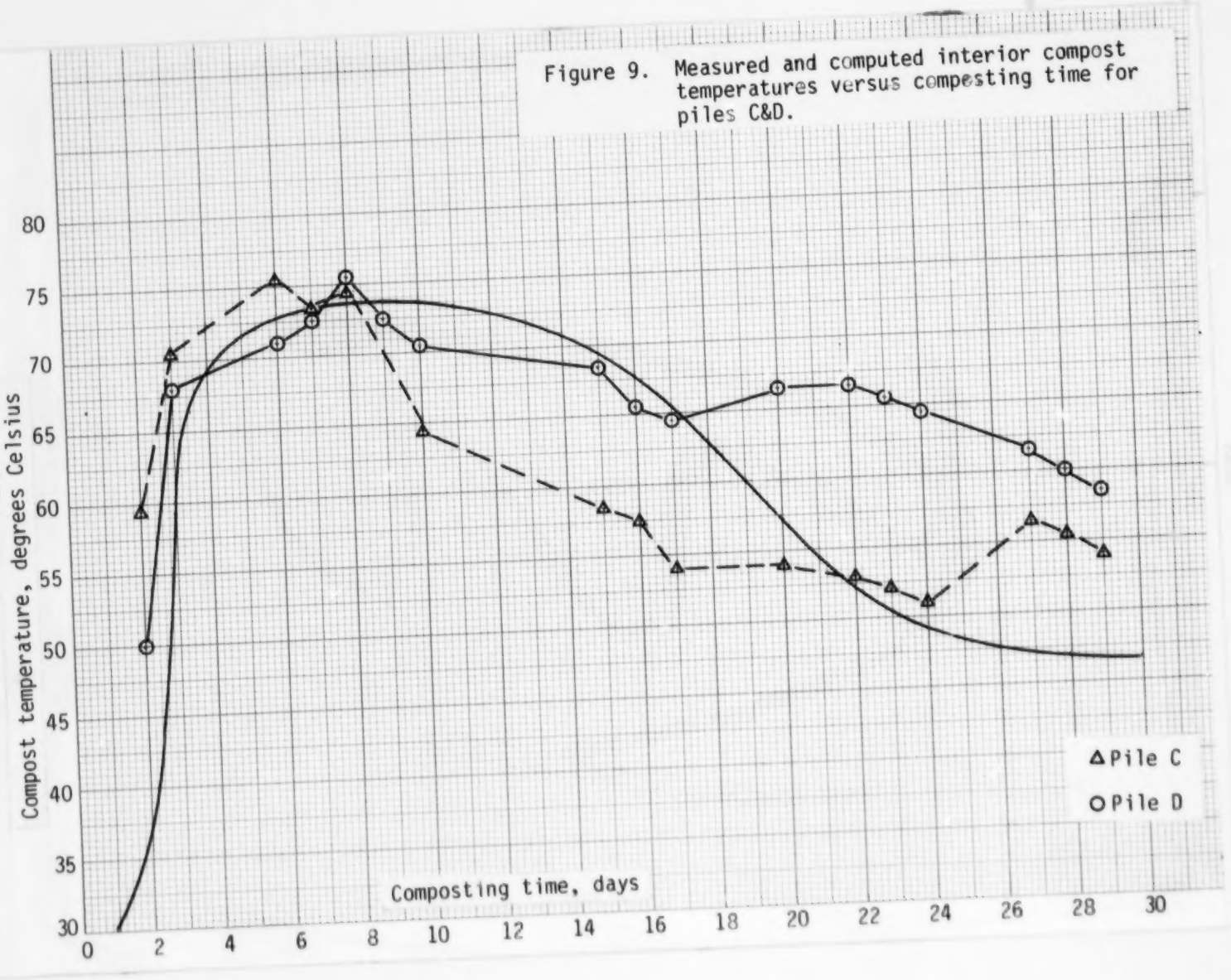


Figure 9. Measured and computed interior compost temperatures versus composting time for piles C&D.

The ratio R has the following values for piles A, B, C, & D.

Pile A	R = 1.2942
Pile B	R = 1.2608
Pile C	R = 1.2868
Pile D	R = 1.2915

These values are relatively consistent between piles and average 1.2834. Thus, it appears that the mass of the piles was reduced by about 22% over the composting period. Partition of this decrease between volume and density cannot be made from available data. However, it seems likely that the density of the initial blend is nearer dry compost than wet cake so that most of the value of R is probably associated with a change in pile volume. If all of the change is associated with volume the linear dimensions of the pile would be changed by the cube root of R or by about 8.7%. Additional measurements of solids and volatile fractions were given in the April, 1978 progress report (11) and using these measurements a value of 1.2445 is found for R. In the March, 1978 progress report (10) five density measurements for wet cake and dry compost were given. Average cake density was 1.044 gm/cm^3 and average dry compost density was 0.85 gm/cm^3. The ratio is 1.228 which further supports the presumption that most of the R ratio is associated with a volume change.

Using the computed R values for each of the four piles the fraction of initial liquid water lost, the fraction of initial volatile solids lost, and the ratio of mass of water lost to mass of volatile solids lost can be computed. The fraction of water lost is computed as 1.0 - (1-FSE)/(1-FSI)/R and computed values are 0.499 for pile A, 0.415 for pile B, 0.444 for pile C and 0.438 for pile D. The average over the four piles was 44.9% of the initial water lost during the composting period. The fraction of volatile solids lost is computed as 1.0 - FSE*FVE/FSI/FVI/R and computed values are 0.0837 for pile A, 0.168 for pile B, 0.0447 for pile C, and 0.0976 for pile D. Grams of water lost divided by grams of volatile solids lost is computed as (R*(1-FSI)-(1-FSE))/(R*FSI*-FVI-FSE*FVE) and this ratio is 14.847 for pile A, 5.914 for pile B, 28.517 for pile C, and 12.756 for pile D. The average of the four values is about 15 mg of water lost per gram of volatile solids lost; a surprisingly high value.

Heat of combustion of volatile sludge solids is usually taken as 10,000 Btu/lb or 5500 cal/gm. However, if the water lost/volatile solids lost ratio is taken as 15 the enthalpy available for evaporation of the water is 5500/15 or 367 cal/gm. If the temperature of the liquid water is 25°C initially the enthalpy change (cal/gm) needed to exhaust the water at temperature T°C is 597.44 + 0.4306(T - 25.) or 572.44 + 0.4306T. Clearly, the heat of combustion must be greater than 5500 cal/gm. If it is assumed that the lipids are first to combust in the composting process the heat of combustion of lipids (9300 cal/gm) can be used in simulating the process. This assumption was made in simulating the behavior of piles A and D. No attempt was made to simulate piles B&C because the water lost/volatile solids lost ratios differed from those computed for piles A&D by roughly a factor of 2.

In the June-July, 1978 LACSD experiments with aerated compost piles the reported pressure drop across the compost was 2-1/2 inches of water or 6.14 mbar. Measured air flow rates through the four piles were given in cfm and these measurements are shown plotted versus the initial solid fractions in Figure 10. In the simulation program the air flow through the pile (ARATE, hr^{-1}) is directly proportional to the constant PDK when PBLOW is fixed. Therefore, slopes of the two regression lines; one relating air flow rate to FS and one relating PDK to FS, should be equal on semi-log paper. These two regression lines with equal slopes are shown in Figure 10. The assumption was, therefore, made that PDK can be estimated using the relationship: PDK = 243,743/EXP(3.4237*FSA). A more precise method would have been to compute a local value of PDK dependent on the local solids fraction but this degree of precision seemed to be unjustified. In simulating the performance of piles A&D the air flow rate was corrected at each time point using the relationship for PDK given above. For example, for pile A the initial value for ARATE was 2.43 hr^{-1} and this decreased as FSA increased over the 30 day composting period to a value of 1.40 hr^{-1}. The initial ARATE for pile D was 2.89 hr^{-1} and this value decreased to 1.54 hr^{-1} at the end of the 30 day composting period. The value for PBLOW was held at 6.14 mbar throughout the composting period but a more precise method would have been to allow PBLOW to increase as the pressure drop gradient increased according to the blower map characteristics. In general, the simulation of the air flow regime seems adequate but better measurements are needed to fully test the linear simulation.

A time interval of 0.25 hours was used in both simulations and the composting period was set at 30 days; thus NT was 2881. Ambient atmospheric air was assumed to have the reported average temperature of 21°C and an average relative humidity of 70%. The relationship between rate of microbiological activity and compost temperature used was the one marked Regan et al in Figure 5. EMIN was set at 0.2 mmole O_2/day per gm of VSS. Actually, in the program the concentration of biodegradable volatile solids was used rather than the concentration of volatile solids. Initial compost temperature (TMIX) was set at 25°C.

The biodegradable fraction of volatile solids decreased from an initial value of FBO = .55 to .49 for pile A and to .47 for pile D. These changes are small compared to the uncertainty associated with the temperature versus biological rate relationship.

The principal difficulty experienced in running the program was the tendency of the blocks along the air-compost boundary to become too dry. This could be caused by omission of the mechanism for moisture movement as a result of capillary pressure or by the assumption that moisture leaving any block is saturated at the block temperature. Correction of this problem should be first priority in the second generation composting model. In running the program this problem was avoided by setting the value of CVE to 3.0, WIND to zero, SOLAR to zero, and HAIRO to 1.25.

The average compost temperature for blocks (7,2) and (8,2) was computed and printed out as the temperature (TAVG) measured in the aerated compost pile experiments. Computed values for TAVG are shown plotted by the solid lines in Figures 8 and 9. The general shape of the curves are similar to the measured points but the agreement is not adequate for predictive purposes. Measurements of fundamental compost characteristics are needed to improve the agreement between measured and computed results.

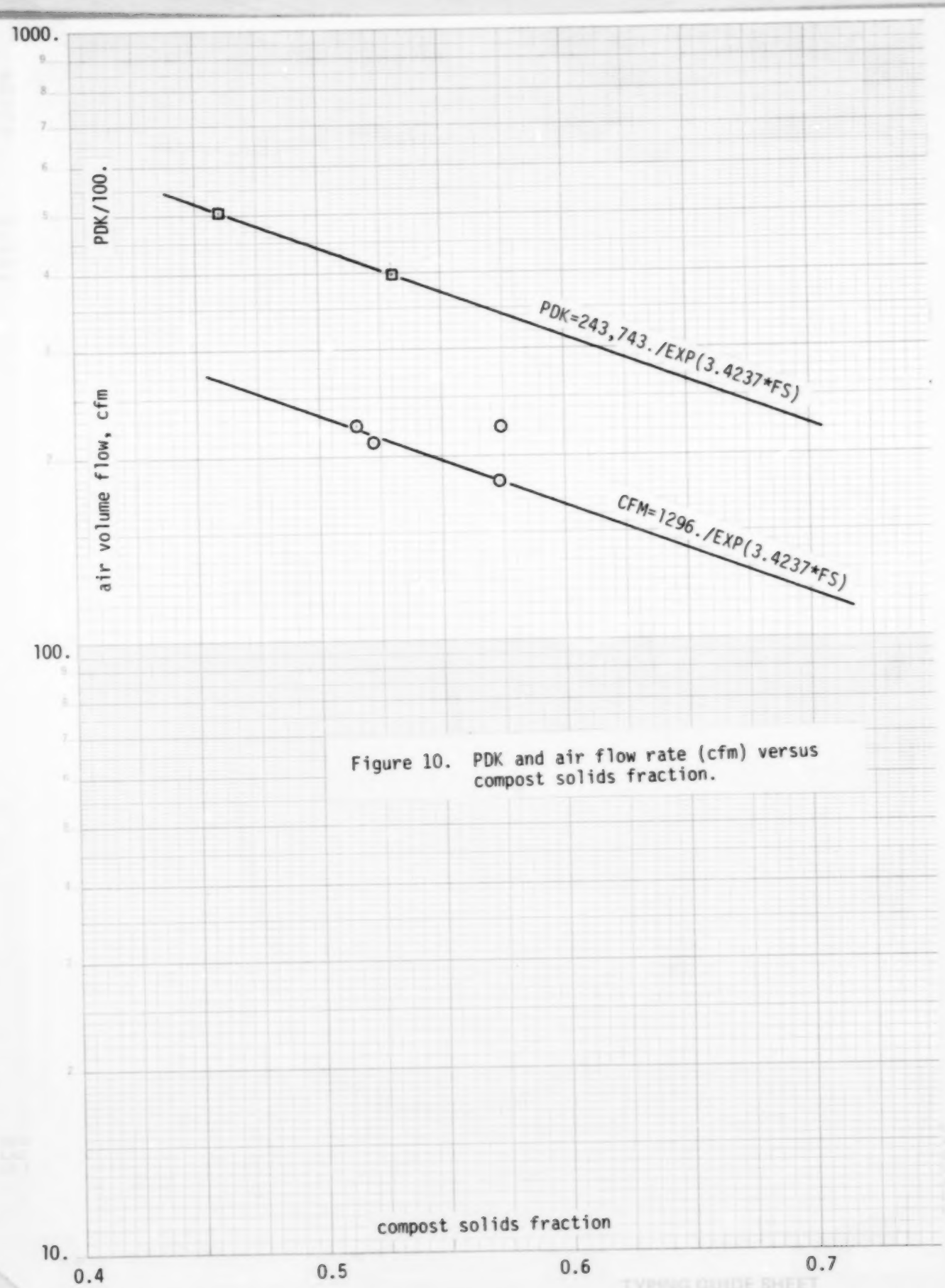


Figure 10. PDK and air flow rate (cfm) versus compost solids fraction.

Other comparisons between computed and measured results are shown in the following table for piles A and D.

	Computed	Measured
Pile A:		
final solids fraction	0.735	0.723
final volatile fraction	0.272	0.281
moisture lost fraction	0.500	0.499
water lost/VSS lost	11.7	14.8
Pile D:		
final solids fraction	0.706	0.653
final volatile fraction	0.272	0.300
moisture lost fraction	0.539	0.438
Water lost/VSS lost	11.8	12.8

These comparative values suggest that the simulation program is doing a reasonably good job of simulating the aerated composting process. However, more detailed measurements of compost properties over the compost period and from various parts of the compost pile will be required to properly assess the validity of the program.

A complete description of the program including the listing and definitions of variables used is given in the appendix.

REFERENCES

1. Epstein, E. and G. B. Willison 1974. Composting Sewage Sludge. In: Proc. National Conference on Municipal Sludge Management, Pittsburgh, Pa.

2. Epstein, E. and G. B. Willison 1975. Composting Raw Sludge. In: Proc. National Conference on Municipal Sludge Management, Anaheim, CA.

3. Epstein, E. et al 1976 A Forced Aeration System for Composting Wastewater Sludge. Jour. Water Pollution Control Federation, Vol. 48, (1976) pp 688-694.

4. Haug, Roger T. 1979. Engineering Principles of Sludge Composting. Jour. Water Pollution Control Federation Vol. 51 (1979) pp 2189-2206.

5. Keenan, J. H. et al., Steam Tables. John Wiley and Sons, Inc. New York (1969).

6. Reid, R. C. and T. K. Sherwood 1958. The Properties of Gases and Liquids. McGraw-Hill Book Co., Inc. New York.

7. Philip, J. R. and D. A. DeVries 1957. Moisture Movement in Porous Materials Under Temperature Gradients. American Geophysical Union Trans. Vol. 38 pp 222-232.

8. Keenan, J. H. and Joseph Kaye 1948. Gas Tables. John Wiley and Sons, Inc. New York.

9. Patten, Harrison E., 1909. Heat Transference in Soils. U.S. Department of Agriculture, Bureau of Soils Bulletin No. 59, U.S. Government Printing Office.

10. Los Angeles County Sanitation Districts and Environmental Protection Agency Joint Research Project Progress Report for March, 1978, EPA Contract No. 14-12-15.

11. LACSD and EPA Joint Research Project Progress Report, April, 1978 EPA Contract No. 14-12-15.

12. DeVries, D. A., 1963. Thermal Properties of Soils. In: W. R. Van Wiejk (ed) Physics of Plant Environment. North-Holland Pub. Co. Amsderdam.

13. McAdams, William H., 1954. Heat Transmission. McGraw-Hill Book Co.

14. LACSD and EPA Joint Research Project Progress Report, October, 1978 EPA Contract No. 14-12-15.

15. Wiley, John S., 1957. Progress Report on High-Rate Composting Studies. Proc. 12'th Industrial Waste Conference (Purdue) pp 596-603.

16. Jeris, J. S. and Raymond W. Regan, 1973. Controlling Environmental Parameters for Optimum Composting. Compost Science Jan-Feb 1973 pp 10-15.

17. Schulze, K. L., 1962. Continuous Thermophilic Composting. Compost Science Spring, 1962 pp 22-31.

18. Arditi, A. 1967 M.Sc. thesis University of Pirmingham In: Review of Composting Part 2-The Practical Process. Process Biochemistry, October 1971.

19. Andrews, John F. and Kawi Kambhu, 1971. Thermophilic Aerobic Digestion of Organic Solid Wastes. Environmental Systems Engineering Dept. Clemson University, South Carolina.

20. Snell, John R., 1957. Some Engineering Aspects of High-Rate Composting. ASCE Jour. Sanitary Engineering Div. February, 1957 paper 1178.

21. Regan, R. et al., 1973. Cellulose Degradation in Composting, USPHS Solid Waste Program Res. Grant UI 00508 PB 215,722 NTIS

22. Schulze, K. L., 1961. Relationship between Moisture Content and Activity of Finished Compost. Compost Science Summer 1961, pp 32-34.

23. Taylor, S. A. and G. L. Ashcroft 1972. Physical Edaphology. W. H. Freeman and Co., San Francisco

24. Chow, Ven Te, 1964. Handbook of Applied Hydrology. McGraw-Hill Book Co., New York.

25. Joint Committee of ASCE and Water Pollution Control Federation, 1959 Sewage Treatment Plant Design. ASCE Manual of Practice No. 36.

26. ASHRAE Handbook of Fundamentals 1972. American Society of Heating, Refrigerating, and Air-Conditioning Engineers.

27. LACSD and EPA Joint Research Project Progress Report, July, 1978 EPA Contract No. 14-12-15.

APPENDIX

Using the Compost Model Computer Program

The compost model computer program is called CMPST and can be used to compute the time-dependent performance of windrow composting of wastewater treatment plant sludge over a specified period of time. NT is the number of time increments of length DT (hours) which the program calculates. The shape of a trapezoidal cross-section is determined by the input variables NVB (number of vertical blocks), NBB (number of base blocks), and NTB (number of surface blocks). DX and DY define the width and height of each interior block of the cross-section. All of these input variables provide the basis for the numerical integration.

Several variables are input to CMPST in order to control what output is printed and how much of it. IT is the number of the time increment at which the program begins to print out the computations; a value of zero begins the printing at time zero. LP specifies the number of time increments that are to be skipped between each print command. IPRNT determines whether the printed output is in fixed or floating decimal format. ITURN defines the number of time increments between the points at which periodic mixing of the compost pile occurs. The input vector IP(I) determines which cross-sectional outputs are printed for each time step. It is possible to obtain a printing of cross-sectional calculations for up to 12 different program output parameters. An input value of zero will suppress the printing of individual parameters. For each parameter that is selected, the computed value of it in each block of the trapezoidal cross-section is printed out at each time increment that is specified. The form of the printout resembles the right half of the compost pile cross-section having I rows and J columns. The left half of the compost pile would be the identical mirror image of the right half. As with any time-dependent computation over a period of time, CMPST is capable of calculating a tremendous amount of output, but the program user can selectively print only the information of interest by setting IT, LP, IPRNT, ITURN, and IP(I) appropriately.

The input variables to CMPST are defined in Table A-1. The FORTRAN names appear in the order in which they are input to the program. Table A-2 gives the definitions of the output parameters that are calculated and printed out by CMPST. Other parameters that are computed and only used internally by the program are also defined in Table A-2. The FORTRAN names appear in the order in which they are printed out by the program. The FORTRAN source code listing for CMPST is given in Table A-3. Sample data for input to the program is shown in Table A-4. Table A-5 gives the respective program output for the data case listed in Table A-4.

CMPST is written completely in FORTRAN and uses no required subroutines or functions. Standard input/output files are used. The computer program was written for a 32K PDP-11/70 computer, but can be easily converted to other systems that have FORTRAN compilers. Since this time-dependent model requires an large amount of intermediate calculations in order to compute the compost pile performance over several days, the program running time is significant. A typical 30-day simulation uses 13.5 minutes of CPU time on the PDP-11/70 computer. A 15-day run would take about half that amount of CPU time, and so on.

Table A-1

INPUT VARIABLES TO CMPST

NCASE	number of data cases to be run
LIST	alpha-numeric identification of each data case
NT	the number of time increments to be computed by the program
IT	number of the time increment at which the program will begin printing output
LP	the number of time increments that the program skips between each print command
IPRNT	program control: 0 prints the program output in F format (fixed decimal point, 1 prints the program output in E format (floating decimal point)
ITURN	the number of time increments that the program skips between each mixing of the compost pile
NBB	number of bottom base blocks in a trapezoidal cross-section of compost pile
NTB	number of top surface blocks in a trapezoidal cross-section of compost pile
NVB	number of vertical blocks in a trapezoidal cross-section of compost pile
DT	length of time increment, hrs
DX	width of areal increment, cm
DY	height of areal increment, cm
TSOIL	ambient soil temperature at a depth of 10 ft, ^{o}C
TAIR	ambient air temperature, ^{o}C
TMIX	initial temperature of the compost, ^{o}C
TWET	ambient air wet bulb temperature, ^{o}C
RH	relative humidity of ambient air, fraction
WIND	ambient wind velocity, miles/hr
WØ	initial compost density, gm/cm^3

FSØ	initial compost solids mass fraction, fraction
FVØ	initial volatile fraction of compost solids, fraction
FBØ	initial biodegradable fraction of compost volatile solids, fraction
TC	compost thermal conductivity, cal/(cm^2)(hr)(^oC/cm)
SPRED	constant used in biological rate versus compost solids fraction relationship
CVE	constant in relationship for surface water evaporation
COMIN	minimum oxygen concentration below which biological activity ceases, gm/cm^3
PBLOW	pressure maintained in pressure source, mbar above or below atmospheric pressure
G	atmospheric pressure change per cm per degree Kelvin, mbar
XAM	average compost porosity, fraction
HSOIL	surface conductance at soil-compost boundary, (cal/hr)/cm^2
EMAX	composting efficiency, mmole O_2/(day)(gm VSS)
EMIN	minimum composting efficiency, mmole O_2/(day)(gm VSS)
WFR	gm water produced per gm fuel combusted
FSPK	solids fraction at which biological activity peaks, fraction
HCOMB	high heat of combustion, cal/gm
SOLAR	adsorbed solar energy, cal/(hr)/(cm^2)
HAIRØ	surface convective heat loss coefficient for wind = 0, (cal/hr)/(cm^2)(^oC)
IP(I)	if IP (1) = 1 print output for T1(I,J) if IP (2) = 2 print output for T2(I,J) if IP (3) = 3 print output for CO1(I,J)/COAIR if IP (4) = 4 print output for CO2(I,J)/COAIR if IP (5) = 5 print output for V(I,J)/VAIR if IP (6) = 6 print output for P(I,J) if IP (7) = 7 print output for UX(I,J)/60./30.48 if IP (8) = 8 print output for UY(I,J)/60./30.48 if IP (9) = 9 print output for W(I,J) if IP(10) = 10 print output for FS(I,J) if IP(11) = 11 print output for FV(I,J) if IP(12) = 12 print output for FB(I,J)

Table A-2

OUTPUT PARAMETERS FROM CMPST

COAIR	oxygen cencentration in ambient air, gm/cm^3
AREA	compost windrow cross-sectional area, cm^2
WPILE	initial water content in one cm thick cross-sectional area, gm
HFUEL	initial fuel value in one cm thick cross-sectional area, kcal
PDK	pressure drop constant from Darcy's law, $cm^2/(mbar)(hr)$
XBLKS	number of blocks in compost half cross-section
I	nodal row number
J	nodal column number
T1(I,J)	local compost temperature at start of DT, ^oC
T2(I,J)	local compost temperature at end of DT, ^oC
CO1(I,J)	local oxygen concentration at start of DT, gm/cm^3
CO2(I,J)	local oxygen concentration at end of DT, gm/cm^3
V(I,J)	local water vapor density, gm/cm^3
P(I,J)	local air pressure, mbar above atmospheric pressure
UX(I,J)	local horizontal air flow velocity positive to right, cm/hr
UY(I,J)	local vertical air flow velocity positive upward, cm/hr
W(I,J)	local compost density, gm/cm^3
FS(I,J)	local compost solids mass fraction
FV(I,J)	local compost volatile mass fraction
FB(I,J)	local compost biodegradable volatile mass fraction
TPILE	average pile temperature, ^oC
WA	average compost density, gm/cm^3
FSA	average compost solids fraction, fraction

FVA	average compost volatile fraction, fraction
FBA	average compost biodegradable fraction, fraction
QHUP	heat lost across compost-air boundary, kcal
QHDWN	heat lost across compost-soil boundary, kcal
QVUP	water lost across compost-air boundary, gm
WSTAR	WOUT - W22, gm
WLOST	water lost from compost one cm slice, gm
W22	water entering pile through block (2,2) gm
WOUT	water lost over air-compost boundary, gm
ARATE	aeration air supplies, $(cm^3/hr)/cm^3$
TAVG	average temperature for blocks (7,2) and (8,2), ^oC
HMIN	HEAT computed with EMIN cal/(hr)(cm^3)
SHMIN	counter showing number of blocks with HEAT = HMIN
HSTAR	HOUT + HSTOR - H22, kcal
HUSED	heat produced by biological activity, kcal
H22	heat entering pile through block (2,2), kcal
HOUT	heat lost over soil and air boundaries, kcal
HSTOR	heat stored in one cm compost slice, kcal
HOFF	number of blocks in which heat = 0 because of lack of oxygen
WLOST/WPILE	fraction of initial pile water lost, fraction
WLOST/HUSED	gm water lost per gm VSS lost

internal program parameters that are calculated but not printed

COAIR	oxygen concentration in ambient air, gm/cm^3
FUELØ	initial concentration of biodegradable organic material, gm/cm^3
HAIR	surface conductance at air-compost boundary, $(cal/hr)/cm^2$

VMIX	saturated water vapor density at TMIX, gm/cm^3
DPAIR	change in atmospheric pressure over DY, mbar
VAIR	water vapor density in ambient air, gm/cm^3
XM	local compost mineral volume fraction
XV	local compost volatile volume fraction
XW	local compost water volume fraction
XA	local compost air volume fraction (porosity)
VHC	local compost volumetric heat capacity, $(cal/cm^3)/^oC$
QHL, QHR QHB, QHT	flux of enthalpy entering any block from the left, right, bottom, and top positive into the block, cal/hr
QVL, QVR, QVB, QVT	flux of water vapor entering any block from the left, right, bottom, and top positive into the block, gm/hr
QOH	oxygen usage rate in any block, gm/hr
HEAT	heat production by microbiological activity, $(cal/hr)/cm^3$
DA	incremental cross-sectional area, cm^2
SPH	heat stored in pile over initial heat, cal

Table A-3

FORTRAN LISTING OF CMPST

```
C  WINDROW COMPOSTING PROCESS MODEL   (CMPST)                3-26-1980
C  RICHARD G. EILERS                  MARCH 1980
C
      DIMENSION T1(20,20),T2(20,20),CO1(20,20),CO2(20,20),
     .          V(20,20),P(20,20),UX(20,20),UY(20,20),W(20,20),
     .          FS(20,20),FV(20,20),VAR(20,20),FB(20,20),
     .          LIST(40),IP(12)
      OPEN(UNIT=1,NAME='CMPST.DAT',TYPE='OLD',FORM='FORMATTED',READONLY)
      CALL ERRSET(63,,.TRUE.,,.FALSE.,,.FALSE.,,.FALSE.,,500)
      CALL ERRSET(72,,.TRUE.,,.FALSE.,,.FALSE.,,.FALSE.,,500)
      CALL ERRSET(73,,.TRUE.,,.FALSE.,,.FALSE.,,.FALSE.,,500)
      IN=1
      IO=4
      READ(IN,5) NCASE
    5 FORMAT(I2)
      DO 1000 III=1,NCASE
      READ(IN,10) LIST
   10 FORMAT(40A2)
      READ(IN,15) XNT,XT,PT,PRNT,TURN,XNBB,XNTB,XNVB
      READ(IN,15) DT,DX,DY,TSOIL,TAIR,TMIX,TWET,WFR
      READ(IN,15) RH,WIND,WO,FSO,FVO,FBO,TC,SPRED
      READ(IN,15) CVE,COMIN,PBLOW,G,XAM,HSOIL,EMAX,EMIN
      READ(IN,15) FSPK,HCOMB,SOLAR,HAIRO
   15 FORMAT(8F10.0)
      READ(IN,20) (IP(I),I=1,12)
   20 FORMAT(12I5)
      NT=XNT
      IT=XT
      LP=PT
      IPRNT=PRNT
      ITURN=TURN
      NBB=XNBB
      NTB=XNTB
      NVB=XNVB
      XBLKS=XNVB*(XNTB+1.)/2.+(XNVB**2+XNVB)/2.-1.
      JB=NBB/2.+1.5
      IV=NVB+1.
      JT=NTB/2.+2.5
      FUELO=WO*FSO*FVO*FBO
      AREA=DX*DY*(NVB*(NVB+NTB)-1.)/2.
      PDK=243743./EXP(3.4237*FSO)
      TK=273.+TMIX
      HAIR=HAIRO+.1674*WIND
      VMIX=EXP(5.84726-4925.89/(TMIX+273.))
      DPAIR=DY*G/(TAIR+273.)
      VAIR=RH*EXP(5.84726-4925.89/(TAIR+273.))
      HFUEL=FUELO*AREA*HCOMB/1000.
      WPILE=(WO*(1.-FSO)+WFR*FUELO)*AREA
      COAIR=.0819/(273.+TAIR)
      FSA=FSO
      IF (PBLOW) 21,22,22
   21 K=1
```

Table A-3 (continued)

```
      GO TO 23
   22 K=0
   23 CONTINUE
C
C  ZERO ALL SUBSCRIPTED VARIABLES
C
      DO 25 I=1,20
      DO 25 J=1,20
      T1(I,J)=TAIR
      T2(I,J)=TAIR
      CO1(I,J)=COAIR
      CO2(I,J)=COAIR
      V(I,J)=VAIR
      P(I,J)=0.
      UX(I,J)=0.
      UY(I,J)=0.
      W(I,J)=0.
      FS(I,J)=0.
      FV(I,J)=0.
      VAR(I,J)=0.
      FB(I,J)=0.
   25 CONTINUE
      WRITE(IO,30) LIST
   30 FORMAT(//,20X,40A2,/)
      WRITE(IO,32) NT,IT,LP,IPRNT,ITURN,NBB,NTB,NVB
   32 FORMAT(9X,'NT',10X,'IT',10X,'LP',7X,'IPRNT',7X,'ITURN',9X,'NBB',
     . 9X,'NTB',9X,'NVB',/,8I12,/)
      WRITE(IO,35) DT,DX,DY,TSOIL,TAIR,TMIX,TWET,WFR
   35 FORMAT(9X,'DT',10X,'DX',10X,'DY',7X,'TSOIL',8X,
     . 'TAIR',8X,'TMIX',8X,'TWET',9X,'WFR',/,8F12.4,/)
      WRITE(IO,40) RH,WIND,WO,FSO,FVO,FBO,TC,SPRED
   40 FORMAT(9X,'RH',8X,'WIND',10X,'WO',9X,'FSO',9X,'FVO',9X,'FBO',
     . 10X,'TC',7X,'SPRED',/,8F12.4,/)
      WRITE(IO,45) CVE,COMIN,PBLOW,G,XAM,HSOIL,EMAX,EMIN
   45 FORMAT(8X,'CVE',7X,'COMIN',7X,'PBLOW',11X,'G',9X,'XAM',7X,
     . 'HSOIL',8X,'EMAX',8X,'EMIN',/,8F12.4,/)
      WRITE(IO,50) FSPK,HCOMB,SOLAR,HAIRO
   50 FORMAT(7X,'FSPK',7X,'HCOMB',7X,'SOLAR',7X,'HAIRO',/,4F12.4,/)
      WRITE(IO,55) (IP(I),I=1,12)
   55 FORMAT(9X,'T1',9X,'T2',8X,'CO1',8X,'CO2',10X,
     . 'V',10X,'P',9X,'UX',9X,'UY',10X,'W',9X,'FS',9X,'FV',9X,'FB',
     . /,6X,'DEG C',6X,'DEG C',2X,'CO1/COAIR',2X,'CO2/COAIR',
     . 5X,'V/VAIR',7X,'MBAR',5X,'FT/MIN',5X,'FT/MIN',
     . 6X,'GM/CC',7X,'SS/W',6X,'VSS/W',6X,'VBS/W',/,12I11,/)
      WRITE(IO,60) COAIR,AREA,WPILE,HFUEL,PDK,XBLKS
   60 FORMAT(6X,'COAIR',8X,'AREA',7X,'WPILE',7X,'HFUEL',9X,'PDK',
     . 7X,'XBLKS',/,F12.7,5F12.4,//)
      WRITE(IO,65)
   65 FORMAT(1X,'I = ROW NUMBER',/,1X,'J = COLUMN NUMBER')
C
C  INITIALIZE ALL SUBSCRIPTED VARIABLES
C
      IND1=JB-1
      IND2=JT-1
```

Table A-3 (continued)

```
      DO 95 J=1,JB
      IF (J-JT) 70,75,75
   70 NR=IV+1
      GO TO 80
   75 NR=NR-1
   80 DO 95 I=1,NR
      IF (I-1) 85,90,85
   85 P(I,J)=DPAIR*(IV-I+.5)
      CO1(I,J)=COAIR
      CO2(I,J)=COAIR
      T1(I,J)=TMIX
      T2(I,J)=TMIX
      V(I,J)=VMIX
      W(I,J)=W0
      FS(I,J)=FS0
      FV(I,J)=FV0
      FB(I,J)=FB0
      GO TO 95
   90 T1(I,J)=TSOIL
      T2(I,J)=TSOIL
   95 CONTINUE
      T1(2,2)=TMIX
      T2(2,2)=TMIX
      V(2,2)=VMIX
      DY2=DY*DY
      DX2=DX*DX
      CY=DY2/(DX2+DY2)/2.
      CX=DX2/(DX2+DY2)/2.
      P(2,2)=PBLOW
      DO 155 IIII=1,200
      DO 100 I=1,IV
      P(I,1)=P(I,3)
  100 CONTINUE
      NRT=IV
      DO 150 J=2,IND1
      NRB=2
      IF (J-JT) 110,105,105
  105 NRT=NRT-1
  110 IF (J-2) 125,120,125
  120 NRB=3
  125 DO 150 I=NRB,NRT
      IF (I-2) 135,130,135
  130 P(2,J)=DY2*(P(2,J+1)+P(2,J-1))/(2.*DY2+DX2)+DX2*
     .       (P(3,J)+DPAIR)/(2.*DY2+DX2)
      GO TO 150
  135 IF (I-IV) 145,140,145
  140 P(IV,J)=DY2*(P(IV,J-1)+P(IV,J+1))/(2.*DY2+3.*DX2)+
     .        DX2*P(IV-1,J)/(2.*DY2+3.*DX2)
      GO TO 150
  145 P(I,J)=CY*(P(I,J+1)+P(I,J-1))+CX*(P(I+1,J)+P(I-1,J))
  150 CONTINUE
  155 CONTINUE
      NRT=IV
      DO 170 J=2,IND1
      NRB=2
```

Table A-3 (continued)

```
      IF (J-JT) 165,160,160
  160 NRT=NRT-1
  165 DO 170 I=NRB,NRT
      UY(I,J)=PDK*(P(I,J)-P(I+1,J))/DY-PDK*DPAIR/DY
      UX(I,J)=PDK*(P(I,J)-P(I,J+1))/DX
  170 CONTINUE
      UX(IV,1)=-UX(IV,2)
      DO 175 J=2,IND2
      UY(IV,J)=UY(IV-1,J)-(UX(IV,J)-UX(IV,J-1))*DY/DX
  175 CONTINUE
      DO 180 J=JT,JB
      I=IV+JT-J
      UX(I,J)=(DY*UX(I,J-1)+DX*UY(I-1,J))*DY/(DX2+DY2)
      UY(I,J)=UX(I,J)*DX/DY
  180 CONTINUE
C
C  PRINT VALUES OF UX,UY
C
      DO 194 II=1,2
      DO 186 I=1,20
      DO 186 J=1,20
      GO TO (182,184),II
  182 VAR(I,J)=UX(I,J)/60./30.48
      IVAR1='UX'
      IVAR2='  '
      GO TO 186
  184 VAR(I,J)=UY(I,J)/60./30.48
      IVAR1='UY'
      IVAR2='  '
  186 CONTINUE
      L1=IV
      NCOL=JT-1
      WRITE(IO,224) IVAR1,IVAR2
      DO 192 I=1,IV
      NCOL=NCOL+1
      WRITE(IO,228) L1,(VAR(L1,J),J=2,NCOL)
      IF (NCOL-JB) 190,188,188
  188 NCOL=JB-1
  190 L1=IV-I
  192 CONTINUE
  194 CONTINUE
      WRITE(IO,195)
  195 FORMAT(///)
C
C  PRINT INITIAL VALUES OF DIMENSIONED VARIABLES
C
      IMIX=0
      QHUP=0.
      QHDWN=0.
      QVUP=0.
      AIRUP=0.
      W22=0.
      H22=0.
      DH201=0.
```

Table A-3 (continued)

```
      DH2O2=0.
      DO 500 II=1,NT
      IMIX=IMIX+1
      IF (II-IT) 290,290,196
  196 TIME=(II-1)*DT
      DAYS=TIME/24.
      IT=IT+LP
      WRITE(IO,198) TIME,DAYS
  198 FORMAT(//,1X,'TIME =',F7.2,1X,'HOURS',2X,F7.2,1X,'DAYS')
      IVAR1='  '
      IVAR2='  '
      DO 280 KK=1,12
      IF (IP(KK)) 280,280,200
  200 DO 220 I=1,20
      DO 220 J=1,20
      GO TO (201,202,203,204,205,206,207,208,209,210,211,212),IP(KK)
  201 VAR(I,J)=T1(I,J)
      IVAR1='T1'
      IVAR2='  '
      GO TO 220
  202 VAR(I,J)=T2(I,J)
      IVAR1='T2'
      IVAR2='  '
      GO TO 220
  203 VAR(I,J)=CO1(I,J)/CDATR
      IVAR1='CO'
      IVAR2='1 '
      GO TO 220
  204 VAR(I,J)=CO2(I,J)/CDATR
      IVAR1='CO'
      IVAR2='2 '
      GO TO 220
  205 VAR(I,J)=V(I,J)/VAIR
      IVAR1='V '
      IVAR2='  '
      GO TO 220
  206 VAR(I,J)=P(I,J)
      IVAR1='P '
      IVAR2='  '
      GO TO 220
  207 VAR(I,J)=UX(I,J)/60./30.48
      IVAR1='UX'
      IVAR2='  '
      GO TO 220
  208 VAR(I,J)=UY(I,J)/60./30.48
      IVAR1='UY'
      IVAR2='  '
      GO TO 220
  209 VAR(I,J)=W(I,J)
      IVAR1='W '
      IVAR2='  '
      GO TO 220
  210 VAR(I,J)=FS(I,J)
      IVAR1='FS'
```

Table A-3 (continued)

```
      IVAR2='  '
      GO TO 220
  211 VAR(I,J)=FV(I,J)
      IVAR1='FV'
      IVAR2='  '
      GO TO 220
  212 VAR(I,J)=FB(I,J)
      IVAR1='FB'
      IVAR2='  '
  220 CONTINUE
      WRITE(IO,224) IVAR1,IVAR2
  224 FORMAT(//,1X,2A2,'I',3X,'J=2',7X,'3',7X,'4',7X,'5',7X,'6',7X,'7',
     . 7X,'8',7X,'9',6X,'10',6X,'11',6X,'12',6X,'13',6X,'14',6X,'15',
     . 6X,'16')
      L1=IV
      NCOL=JT-1
      DO 260 I=1,IV
      NCOL=NCOL+1
      IF (IPRNT) 230,226,230
  226 WRITE(IO,228) L1,(VAR(L1,J),J=2,NCOL)
  228 FORMAT(I6,16F8.4)
      GO TO 235
  230 WRITE(IO,232) L1,(VAR(L1,J),J=2,NCOL)
  232 FORMAT(I6,16E8.2)
  235 IF(NCOL-JB) 250,240,240
  240 NCOL=JB-1
  250 L1=IV-I
  260 CONTINUE
  280 CONTINUE
      WRITE(IO,285) TPILE,WA,FSA,FVA,FBA,QHUP,QHDWN,QVUP,
     .              WSTAR,WLOST,W22,WOUT,ARATE,TAVG,HMIN,SHMIN,
     .              HSTAR,HUSED,H22,HOUT,HSTOR,HOFF,WP,HR
  285 FORMAT(/,9X,'TPILE',14X,'WA',13X,'FSA',13X,'FVA',13X,'FBA',12X,
     . 'QHUP',11X,'QHDWN',12X,'QVUP',/,8F16.5,/,9X,'WSTAR',11X,
     . 'WLOST',13X,'W22',12X,'WOUT',11X,'ARATE',12X,'TAVG',12X,
     . 'HMIN',11X,'SHMIN',/,8F16.5,/,9X,'HSTAR',11X,'HUSED',13X,
     . 'H22',12X,'HOUT',11X,'HSTOR',12X,'HOFF',5X,'WLOST/WPILE',
     . 5X,'WLOST/HUSED',/,8F16.5)
C
C  INITIALIZE LEFT BOUNDRY NODES
C
      IIV=IV+1
  290 DO 300 I=3,IIV
      V(I,1)=V(I,2)
      T1(I,1)=T1(I,2)
      UX(I,1)=-UX(I,2)
      UY(I,1)=UY(I,2)
      CO1(I,1)=CO2(I,2)
  300 CONTINUE
C
C  SOLVE FOR ALL VARIABLES AT LATER TIME
C
      SPH=0.
      SVHC=0.
```

Table A-3 (continued)

```
      WGT=0.
      SOL=0.
      PH2O=0.
      VSOL=0.
      VBSOL=0.
      HOFF=0.
      SHMIN=0.
      DXDY=DX*DY
      NRT=IV
      AIRIN=DY*UX(2,2)+DX*UY(2,2)/2.
      ARATE=AIRIN/AREA
      IF (PBLOW) 304,302,302
  302 T1(2,2)=TAIR
      V(2,2)=VAIR
  304 DV=(803.+8.81*(T1(3,2)+T1(2,2))/2.)*XAM
      WTOP=DX/2.*(UY(2,2)*V(2+K,2)-DV*(V(3,2)-V(2,2))/DY)
      DV=(803.+8.81*(T1(2,3)+T1(2,2))/2.)*XAM
      WRGT=DY*(UX(2,2)*V(2,2+K)-DV*(V(2,3)-V(2,2))/DX)
      W22=W22+(WTOP+WRGT)*DT
      HTOP=DX/2.*(.08442*UY(2,2)*T1(2+K,2)/(T1(2+K,2)+273.))+
     .     WTOP*(597.44+.4306*T1(2+K,2))
      HRGT=DY*(.08442*UX(2,2)*T1(2,2+K)/(T1(2,2+K)+273.))+
     .     WRGT*(597.44+.4306*T1(2,2+K))
      H22=H22+(HTOP+HRGT)*DT/1000.
      DO 400 J=2,JB
      NRB=2
      IF (J-JT) 315,315,305
  305 NRT=NRT-1
  315 IF (J-2) 325,320,325
  320 NRB=3
  325 DO 400 I=NRB,NRT
      DA=DXDY
      XM=FS(I,J)*(1.-FV(I,J))*WO/2.65
      XV=FS(I,J)*FV(I,J)*WO/1.3
      XW=(1.-FS(I,J))*WO
      XA=1.-XM-XV-XW
      VHC=.46*XM+.6*XV+XW
      IF (CO1(I,J)/COAIR-COMIN) 330,330,332
  330 HEAT=0.
      HOFF=HOFF+1.
      GO TO 336
  332 HMIN=HCOMB/1200.*EMIN*W(I,J)*FS(I,J)*FV(I,J)*FB(I,J)
      HEAT=HCOMB/1200.*EMAX*W(I,J)*FS(I,J)*FV(I,J)*FB(I,J)/
     .     EXP((T1(I,J)-57.)**2/254.)/EXP(SPRED*(FS(I,J)-FSPK)**2)
  333 IF (HEAT-HMIN) 335,335,336
  335 HEAT=HMIN
      SHMIN=SHMIN+1.
  336 DV=(803.+8.81*(T1(I,J)+T1(I,J-1))/2.)*XAM
      DVOL=HEAT*DT/HCOMB
      QVL=DY*(UX(I,J-1)*V(I,J-1+K)+DV*(V(I,J-1)-V(I,J))/DX)
      DV=(803.+8.81*(T1(I,J)+T1(I,J+1))/2.)*XAM
      QVR=DY*(-UX(I,J)*V(I,J+K)+DV*(V(I,J+1)-V(I,J))/DX)
      DV=(803.+8.81*(T1(I,J)+T1(I-1,J))/2.)*XAM
      QVB=DX*(UY(I-1,J)*V(I-1+K,J)+DV*(V(I-1,J)-V(I,J))/DY)
```

Table A-3 (continued)

```
      DV=(803.+8.81*(T1(I,J)+T1(I+1,J))/2.)*XAM
      QVT=DX*(-UY(I,J)*V(I+K,J)+DV*(V(I+1,J)-V(I,J))/DY)
      RBF=1.
      TBF=1.
  340 IF (I-NRT) 348,342,348
  342 IF (J-JT) 344,346,346
  344 TBF=2.
      GO TO 348
  346 RBF=3.
      TBF=3.
  348 DOL=DY*(625.8+3.74*(T1(I,J)+T1(I,J-1))/2.)*XAM/DX
      DOR=DY*(625.8+3.74*(T1(I,J)+T1(I,J+1))/2.)*XAM/DX*RBF
      DOB=DX*(625.8+3.74*(T1(I,J)+T1(I-1,J))/2.)*XAM/DY
      DOT=DX*(625.8+3.74*(T1(I,J)+T1(I+1,J))/2.)*XAM/DY*TBF
      QDOIN=DOL*CO1(I,J-1)+DOR*CO1(I,J+1)+DOB*CO1(I-1,J)+DOT*CO1(I+1,J)
      QOH=HEAT*DA*1.6/HCOMB
      IF (PBLOW) 349,350,350
  349 QOIN=QDOIN-DY*UX(I,J)*CO1(I,J+1)-DX*UY(I,J)*CO1(I+1,J)
      QOUT=DOL+DOR+DOB+DOT-DY*UX(I,J-1)-DX*UY(I-1,J)
      GO TO 351
  350 QOIN=QDOIN+DY*UX(I,J-1)*CO1(I,J-1)+DX*UY(I-1,J)*CO1(I-1,J)
      QOUT=DOL+DOR+DOB+DOT+DY*UX(I,J)+DX*UY(I,J)
  351 A=(QOIN-QOH)/DA
      B=QOUT/DA
      CO2(I,J)=A*(1.-1./EXP(B*DT))/B+CO1(I,J)/EXP(B*DT)
      IF (I-2) 353,352,353
  352 QVB=0.
  353 IF (I-NRT) 359,354,359
  354 IF (J-JT) 356,358,358
  356 QVT=.482*CVE*(1.+WIND/10.)*DX*(VAIR*(TAIR+273.)-V(I,J)*
     .    (T1(I,J)+273.))-UY(I,J)*V(I+K,J)*DX
      GO TO 359
  358 QVT=.482*CVE*(1.+WIND/10.)*(2.*CX)**.5*(VAIR*(TAIR+273.)-
     .    V(I,J)*(T1(I,J)+273.))*DX-UY(I,J)*V(I+K,J)*DX
      QVR=.482*CVE*(1.+WIND/10.)*(2.*CY)**.5*(VAIR*(TAIR+273.)-
     .    V(I,J)*(T1(I,J)+273.))*DY-UX(I,J)*V(I,J+K)*DY
  359 QHL=TC*(T1(I,J-1)-T1(I,J))*DY/DX+QVL*(597.44+.4306*T1(I,J-1+K)
     .    )+UX(I,J-1)*.08442*DY*T1(I,J-1+K)/(T1(I,J-1+K)+273.)
      QHR=TC*(T1(I,J+1)-T1(I,J))*DY/DX+QVR*(597.44+.4306*T1(I,J+K)
     .    )-UX(I,J)*.08442*DY*T1(I,J+K)/(T1(I,J+K)+273.)
      QHB=TC*(T1(I-1,J)-T1(I,J))*DX/DY+QVB*(597.44+.4306*T1(I-1+K,J)
     .    )+UY(I-1,J)*.08442*DX*T1(I-1+K,J)/(T1(I-1+K,J)+273.)
      QHT=TC*(T1(I+1,J)-T1(I,J))*DX/DY+QVT*(597.44+.4306*T1(I+K,J)
     .    )-UY(I,J)*.08442*DX*T1(I+K,J)/(T1(I+K,J)+273.)
      IF (I-NRB) 372,362,372
  362 IF (J-3) 364,366,370
  364 QHB=HTOP*2.
      GO TO 372
  366 QHL=HRGT
  370 QHB=HSOIL*(TSOIL-T1(I,J))*DX
      QHDWN=QHDWN-QHB*DT
  372 IF (I-NRT) 384,375,384
  375 IF (J-JT) 380,382,382
  380 QHT=(HAIR*(TAIR-T1(I,J))+SOLAR)*DX+QVT*(597.44+.4306*T1(I+K,J)
     .    )-UY(I,J)*.08442*DX*T1(I+K,J)/(273.+T1(I+K,J))
```

Table A-3 (continued)

```
      QHUP=QHUP-QHT*DT
      QVUP=QVUP-QVT*DT
      GO TO 384
  382 QHT=(HAIR*(TAIR-T1(I,J))+SOLAR)*DX*(2.*CX)**.5+QVT*(597.44+.4306*
     .    T1(I+K,J))-UY(I,J)*.08442*DX*T1(I+K,J)/(273.+T1(I+K,J))
      QHR=(HAIR*(TAIR-T1(I,J))+SOLAR)*DY*(2.*CY)**.5+QVR*(597.44+.4306*
     .    T1(I,J+K))-UX(I,J)*.08442*DY*T1(I,J+K)/(273.+T1(I,J+K))
      QHUP=QHUP-(QHT+QHR)*DT
      QVUP=QVUP-(QVT+QVR)*DT
      DA=DXDY/2.
  384 IF (J-2) 386,385,386
  385 QVL=QVR
      QHL=QHR
  386 T2(I,J)=T1(I,J)+DT*(QHL+QHR+QHB+QHT)/VHC/DA+HEAT*DT/VHC
      DH2O=-(QVL+QVR+QVB+QVT)*DT/DA-DVOL*WFR
      IF (T2(I,J)-TWET) 387,393,393
  387 T2(I,J)=TWET
  393 TK=T2(I,J)+273.
      VTEMP=EXP(5.8472-4925.89/TK)
      DVOL=HEAT*DT/HCOMB
      FB(I,J)=(W(I,J)*FS(I,J)*FV(I,J)*FB(I,J)-DVOL)/(W(I,J)*FS(I,J)*
     .        FV(I,J)-DVOL)
      FV(I,J)=(W(I,J)*FS(I,J)*FV(I,J)-DVOL)/(W(I,J)*FS(I,J)-DVOL)
      FS(I,J)=(W(I,J)*FS(I,J)-DVOL)/(W(I,J)-DVOL-DH2O)
      W(I,J)=W(I,J)-DVOL-DH2O
      IF (J-2) 397,396,397
  396 DA=DXDY/2.
  397 TEMP1=W(I,J)*DA
      WGT=WGT+TEMP1
      TEMP2=TEMP1*FS(I,J)
      SOL=SOL+TEMP2
      PH2O=PH2O+TEMP1-TEMP2
      TEMP3=TEMP2*FV(I,J)
      VSOL=VSOL+TEMP3
      TEMP4=TEMP3*FB(I,J)
      VBSOL=VBSOL+TEMP4
      SPH=SPH+VHC*(T2(I,J)-TMIX)*DA
      SVHC=SVHC+VHC*DA
      IF (II-IT) 400,398,398
  398 CT=CO2(I,J)/COAIR
  400 CONTINUE
      WA=WGT/AREA
      TEMP=FSA
      FSA=SOL/WGT
      DFSA=FSA-TEMP
      FVA=VSOL/SOL
      FBA=VBSOL/VSOL
      TEMP=(.241*CVE*(1.+WIND/10.)*DX*(V(IV,2)*(T1(IV,2)+273.)-
     .     VAIR*(TAIR+273.))+UY(IV,2)*V(IV,2)*DX/2.)*DT
      QVUP=QVUP-TEMP
      QHUP=QHUP-DX/2.*(.8442*UY(IV,2)*T1(IV,2)/(T1(IV,2)+273.)+
     .     HAIR*(T1(IV,2)-TAIR))*DT-TEMP*(597.44+.4306*T1(IV,2))
      FUELA=VBSOL/AREA
      HSTOR=SPH/1000.
```

Table A-3 (continued)

```
      HOUT=(QHUP+QHDWN)/1000.
      HSTAR=HOUT+HSTOR-H22
      HUSED=(FUEL0-FUELA)*AREA*HCOMB/1000.
      WOUT=QVUP
      WLOST=WPILE-PH2O-VBSOL*WFR
      TPILE=SPH/SVHC+TMIX
      TK=TPILE+273
      VA=EXP(5.84726-4925.89/TK)
      HR=WLOST*HCOMB/(HUSED-HSTOR)/1000.
      WR=WLOST/WPILE
      WSTAR=WOUT-W22
      TAVG=(T2(7,2)+T2(8,2))/2.
      V(2,2)=(WTOP+WRGT)/(DX*UY(2,2)/2.+DY*UX(2,2))
      TEMP=(T1(3,2)+T1(2,3))/2.+273.
      A=HTOP+HRGT-(WTOP+WRGT)*597.44
      B=.4306*(WTOP+WRGT)+.08442*(DX/2.*UY(2,2)+DY*UX(2,2))/TEMP
      T1(2,2)=A/B
      UF=1./EXP(3.4237*DFSA)
      UX(2,2)=UX(2,2)*UF
      UY(2,2)=UY(2,2)*UF
C
C  INITIALIZE ALL SUBSCRIPTED VARIABLES TO EARLIER TIME
C
      NRT=IV
      DO 490 J=2,JB
      NRB=2
      IF (J-JT) 415,415,410
  410 NRT=NRT-1
  415 IF (J-2) 430,420,430
  420 NRB=3
  430 DO 490 I=NRB,NRT
      IF (ITURN-IMIX) 440,440,450
  440 FS(I,J)=FSA
      FV(I,J)=FVA
      FB(I,J)=FBA
      W(I,J)=WA
      T1(I,J)=TPILE
      CO1(I,J)=COAIR
      V(I,J)=VA
      GO TO 490
  450 TK=T2(I,J)+273.
      V(I,J)=EXP(5.84726-4925.89/TK)
      T1(I,J)=T2(I,J)
      UX(I,J)=UF*UX(I,J)
      UY(I,J)=UF*UY(I,J)
      CO1(I,J)=CO2(I,J)
  490 CONTINUE
      IF (ITURN-IMIX) 495,495,500
  495 IMIX=0
  500 CONTINUE
 1000 CONTINUE
      CLOSE(UNIT=1)
      END
```

Table A-4

INPUT DATA TO CMPST

```
1
          COMPOST MODEL - "PILE D"          3-26-1980
  2881.          0.          480.          0.          4000.          29.          5.          12.
   .25         20.83        20.83         4.5           21.           25.         17.          .54
   .7             0.         .8665        .5220         .3220         .5500        3.6        10.973
   3.           .25          -6.14        .3467          .45          .0651        3.7          .2
   .3         9300.             0.        1.25
 1    0     0     0     0     0     0     0     0     0    10     0     0
```

Table A-5

PRINTED OUTPUT FROM CMPST

COMPOST MODEL = "PILE D" 3-26-1980

NT	IT	LP	IPRNT	ITURN	NBR	NTB	NVB
2881	0	480	0	4000	29	5	12

DT	DX	DY	TSOIL	TAIR	TMIX	TWET	WFR
0.2500	20.8300	20.8300	4.5000	21.0000	25.0000	17.0000	0.5400

RH	WIND	WO	FSO	FVO	FBO	TC	SPRED
0.7000	0.0000	0.8665	0.5220	0.3220	0.5500	3.6000	10.9730

CVE	COMIN	PRLOW	G	XAM	HSOIL	EMAX	EMIN
3.0000	0.2500	-6.1400	0.3467	0.4500	0.0651	3.7000	0.2000

FSPK	HCOMB	SOLAR	HAIRO
0.3000	9300.0000	0.0000	1.2500

T1	T2	CO1	CO2	V	P	UX	UY	W	FS	FV	FB
DEG C	DEG C	CO1/COAIR	CO2/COAIR	V/VAIR	MBAR	FT/MIN	FT/MIN	GM/CC	BS/M	VBS/M	VBS/M
1	0	0	0	0	0	0	0	0	10	0	0

COAIR	AREA	WPILE	HFUEL	PDR	XBLKS
0.0002786	44039.7227	70145.6855	32808.4102	40810.6445	113.0000

I = ROW NUMBER
J = COLUMN NUMBER

UX

I	J=2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
13	-0.0049	-0.0182	-0.0494	-0.0797											
12	-0.0114	-0.0365	-0.0892	-0.1101	-0.1280										
11	-0.0155	-0.0472	-0.0908	-0.1151	-0.1460	-0.1590									
10	-0.0189	-0.0562	-0.0916	-0.1237	-0.1507	-0.1720	-0.1798								
9	-0.0230	-0.0670	-0.1057	-0.1373	-0.1613	-0.1778	-0.1875	-0.1892							
8	-0.0292	-0.0832	-0.1269	-0.1586	-0.1792	-0.1904	-0.1939	-0.1909	-0.1864						
7	-0.0397	-0.1096	-0.1601	-0.1911	-0.2066	-0.2107	-0.2068	-0.1968	-0.1819	-0.1721					
6	-0.0599	-0.1553	-0.2178	-0.2392	-0.2452	-0.2390	-0.2257	-0.2078	-0.1866	-0.1623	-0.1487				
5	-0.1044	-0.2390	-0.2986	-0.3077	-0.2961	-0.2746	-0.2492	-0.2222	-0.1943	-0.1653	-0.1350	-0.1191			
4	-0.2233	-0.3997	-0.4267	-0.3990	-0.3568	-0.3140	-0.2742	-0.2375	-0.2030	-0.1696	-0.1366	-0.1032	-0.0863		
3	-0.6124	-0.7096	-0.6117	-0.5048	-0.4182	-0.3504	-0.2961	-0.2506	-0.2106	-0.1737	-0.1384	-0.1038	-0.0693	-0.0520	
2	-2.1290	-1.2148	-0.8056	-0.5904	-0.4607	-0.3735	-0.3093	-0.2583	-0.2150	-0.1761	-0.1396	-0.1043	-0.0694	-0.0347	-0.0174
1	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

UY

I	J=2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
13	-0.1449	-0.1350	-0.0987	-0.0797											
12	-0.1547	-0.1483	-0.1299	-0.1101	-0.1280										
11	-0.1775	-0.1734	-0.1696	-0.1510	-0.1460	-0.1590									
10	-0.2086	-0.2051	-0.1982	-0.1854	-0.1768	-0.1720	-0.1798								
9	-0.2465	-0.2424	-0.2316	-0.2175	-0.2038	-0.1933	-0.1875	-0.1892							
8	-0.2926	-0.2864	-0.2703	-0.2491	-0.2278	-0.2098	-0.1972	-0.1909	-0.1864						
7	-0.3510	-0.3405	-0.3141	-0.2809	-0.2484	-0.2210	-0.2008	-0.1879	-0.1819	-0.1721					
6	-0.4305	-0.4104	-0.3647	-0.3120	-0.2639	-0.2252	-0.1969	-0.1779	-0.1670	-0.1623	-0.1487				
5	-0.5504	-0.5059	-0.4222	-0.3384	-0.2699	-0.2191	-0.1835	-0.1601	-0.1457	-0.1380	-0.1350	-0.1191			
4	-0.7594	-0.6405	-0.4798	-0.3496	-0.2583	-0.1976	-0.1582	-0.1331	-0.1178	-0.1091	-0.1048	-0.1032	-0.0863		
3	-1.2060	-0.8169	-0.5070	-0.3220	-0.2162	-0.1548	-0.1184	-0.0965	-0.0833	-0.0758	-0.0717	-0.0699	-0.0693	-0.0520	
2	-2.4309	-0.9142	-0.4891	-0.2152	-0.1296	-0.0871	-0.0641	-0.0510	-0.0433	-0.0389	-0.0365	-0.0353	-0.0348	-0.0347	-0.0174
1	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

Table A-5 (continued)

TIME = 0.00 HOURS 0.00 DAYS

TI	I	J=2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
	13	25.0000	25.0000	25.0000	25.0000											
	12	25.0000	25.0000	25.0000	25.0000	25.0000										
	11	25.0000	25.0000	25.0000	25.0000	25.0000	25.0000									
	10	25.0000	25.0000	25.0000	25.0000	25.0000	25.0000	25.0000								
	9	25.0000	25.0000	25.0000	25.0000	25.0000	25.0000	25.0000	25.0000							
	8	25.0000	25.0000	25.0000	25.0000	25.0000	25.0000	25.0000	25.0000	25.0000						
	7	25.0000	25.0000	25.0000	25.0000	25.0000	25.0000	25.0000	25.0000	25.0000	25.0000					
	6	25.0000	25.0000	25.0000	25.0000	25.0000	25.0000	25.0000	25.0000	25.0000	25.0000	25.0000				
	5	25.0000	25.0000	25.0000	25.0000	25.0000	25.0000	25.0000	25.0000	25.0000	25.0000	25.0000	25.0000			
	4	25.0000	25.0000	25.0000	25.0000	25.0000	25.0000	25.0000	25.0000	25.0000	25.0000	25.0000	25.0000	25.0000		
	3	25.0000	25.0000	25.0000	25.0000	25.0000	25.0000	25.0000	25.0000	25.0000	25.0000	25.0000	25.0000	25.0000	25.0000	
	2	25.0000	25.0000	25.0000	25.0000	25.0000	25.0000	25.0000	25.0000	25.0000	25.0000	25.0000	25.0000	25.0000	25.0000	25.0000
	1	4.5000	4.5000	4.5000	4.5000	4.5000	4.5000	4.5000	4.5000	4.5000	4.5000	4.5000	4.5000	4.5000	4.5000	4.5000

FS	I	J=2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
	13	0.5220	0.5220	0.5220	0.5220											
	12	0.5220	0.5220	0.5220	0.5220	0.5220										
	11	0.5220	0.5220	0.5220	0.5220	0.5220	0.5220									
	10	0.5220	0.5220	0.5220	0.5220	0.5220	0.5220	0.5220								
	9	0.5220	0.5220	0.5220	0.5220	0.5220	0.5220	0.5220	0.5220							
	8	0.5220	0.5220	0.5220	0.5220	0.5220	0.5220	0.5220	0.5220	0.5220						
	7	0.5220	0.5220	0.5220	0.5220	0.5220	0.5220	0.5220	0.5220	0.5220	0.5220					
	6	0.5220	0.5220	0.5220	0.5220	0.5220	0.5220	0.5220	0.5220	0.5220	0.5220	0.5220				
	5	0.5220	0.5220	0.5220	0.5220	0.5220	0.5220	0.5220	0.5220	0.5220	0.5220	0.5220	0.5220			
	4	0.5220	0.5220	0.5220	0.5220	0.5220	0.5220	0.5220	0.5220	0.5220	0.5220	0.5220	0.5220	0.5220		
	3	0.5220	0.5220	0.5220	0.5220	0.5220	0.5220	0.5220	0.5220	0.5220	0.5220	0.5220	0.5220	0.5220	0.5220	
	2	0.5220	0.5220	0.5220	0.5220	0.5220	0.5220	0.5220	0.5220	0.5220	0.5220	0.5220	0.5220	0.5220	0.5220	0.5220
	1	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

TPILE	WA	FSA	FVA	FBA	QHUP	QHDWN	QVUP
0.00000	0.00000	0.52200	0.00000	0.00000	0.00000	0.00000	0.00000
WSTAR	WLOST	W22	WOUT	ARATE	TAVG	HMIN	SHMIN
0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
HSTAR	WUSED	H22	HOUT	HSTOR	HOFF	WLOST/WPILE	WLOST/WUSED
0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000

TIME = 120.00 HOURS 5.00 DAYS

TI	I	J=2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
	13	23.1334	23.0130	22.5693	20.8511											
	12	33.0883	32.0277	29.5647	26.0596	20.8591										
	11	54.2017	49.8196	39.2009	30.9322	25.5375	20.6692									
	10	63.6975	61.1036	53.5008	38.2465	29.6099	24.8158	20.5291								
	9	68.2401	66.2144	60.4943	48.1641	34.0642	28.3249	24.3828	20.4674							
	8	70.8062	68.9442	64.1540	55.2555	40.5289	31.8457	27.7851	24.2912	20.4849						
	7	72.3353	70.4747	66.2176	59.4280	48.4567	37.1444	31.4133	27.9253	24.5260	20.5796					
	6	73.1852	71.2608	67.4519	62.3282	55.3426	46.3159	37.9837	32.4420	28.7527	25.0887	20.7456				
	5	73.4900	71.5481	68.2439	64.8589	61.0599	56.6914	51.0564	43.0158	35.4347	30.2038	25.9050	20.9596			
	4	73.3048	71.5888	69.3130	67.4313	65.7814	64.0099	61.5802	57.6207	50.5586	39.2061	31.4818	26.7057	21.1584		
	3	72.8329	71.7664	70.6890	70.1104	69.6242	68.8700	67.5228	65.1393	60.8006	52.1848	38.2488	31.3169	26.8637	21.1650	
	2	72.2801	71.9488	71.6703	71.5229	71.1688	70.4220	69.0843	66.7584	62.4496	53.3240	37.6324	31.3649	28.1495	24.6146	20.4607
	1	4.5000	4.5000	4.5000	4.5000	4.5000	4.5000	4.5000	4.5000	4.5000	4.5000	4.5000	4.5000	4.5000	4.5000	4.5000

Table A-5 (continued)

FS	I	J=2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
	13	0.5293	0.5293	0.5298	0.5546											
	12	0.5281	0.5280	0.5277	0.5283	0.5612										
	11	0.5336	0.5316	0.5286	0.5286	0.5297	0.5644									
	10	0.5488	0.5477	0.5385	0.5296	0.5295	0.5302	0.5664								
	9	0.5512	0.5533	0.5509	0.5358	0.5296	0.5298	0.5305	0.5673							
	8	0.5483	0.5524	0.5561	0.5466	0.5320	0.5296	0.5300	0.5305	0.5671						
	7	0.5448	0.5502	0.5574	0.5551	0.5393	0.5306	0.5296	0.5299	0.5304	0.5657					
	6	0.5423	0.5487	0.5574	0.5600	0.5508	0.5374	0.5309	0.5295	0.5297	0.5301	0.5634				
	5	0.5412	0.5483	0.5570	0.5614	0.5595	0.5517	0.5411	0.5327	0.5294	0.5292	0.5295	0.5604			
	4	0.5418	0.5486	0.5553	0.5585	0.5590	0.5574	0.5536	0.5463	0.5355	0.5289	0.5281	0.5283	0.5567		
	3	0.5443	0.5474	0.5500	0.5501	0.5497	0.5494	0.5491	0.5476	0.5423	0.5319	0.5265	0.5262	0.5264	0.5520	
	2	0.5220	0.5322	0.5332	0.5325	0.5325	0.5330	0.5338	0.5338	0.5312	0.5243	0.5219	0.5223	0.5226	0.5228	0.5439
	1	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

TPILE	WA	FSA	FVA	FBA	QHUP	QHDWN	QVUP
47.66945	0.83100	0.53950	0.31597	0.53734	-129290.61719	73070.13281	-93.27114
WSTAR	WLOST	W22	WOUT	ARATE	TAVG	HMIN	SHMIN
1481.75452	1482.59583	-1575.02563	-93.27114	-2.72543	71.57077	0.12171	42.00000
HSTAR	HUSED	H22	HOUT	HSTOR	HOFF	WLOST/WPILE	WLOST/HUSED
1637.69470	1632.19019	-1172.22510	-56.22049	521.69006	0.00000	0.07359	12.41615

TIME = 240.00 HOURS 10.00 DAYS

TI	I	J=2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
	13	25.7327	25.6049	24.7543	21.5825											
	12	56.0941	55.6445	51.2920	33.9422	21.7990										
	11	64.9705	64.1338	60.3377	49.7168	30.9462	21.2748									
	10	69.1686	68.0202	64.2561	56.4122	40.6688	27.7668	20.8984								
	9	71.6060	70.2288	66.4593	60.0141	49.4175	33.9770	26.1576	20.7532							
	8	73.1278	71.5642	67.8053	62.2692	54.6190	42.7892	31.8943	25.9151	20.8082						
	7	74.0562	72.3183	68.6375	63.9056	58.3447	51.2130	41.5206	32.6997	26.9057	21.0964					
	6	74.5214	72.6254	69.1534	65.3310	61.5375	57.6215	53.0007	46.6525	37.5616	29.7432	21.6566				
	5	74.5586	72.5951	69.5917	66.8884	64.6813	62.7748	60.8123	58.3366	54.6026	47.8145	34.1948	22.6992			
	4	74.1834	72.4384	70.3161	68.9269	68.0982	67.4788	66.7679	65.7275	64.0805	61.2643	55.8058	43.1169	23.9368		
	3	73.6256	72.5843	71.7172	71.5541	71.6501	71.6833	71.4951	71.0056	70.1342	68.7108	66.2802	61.5324	49.4204	23.4242	
	2	73.2322	72.9819	72.9987	73.2561	73.4295	73.4235	73.2290	72.8466	72.2584	71.3960	70.0530	67.5925	61.4899	33.3448	21.1178
	1	4.5000	4.5000	4.5000	4.5000	4.5000	4.5000	4.5000	4.5000	4.5000	4.5000	4.5000	4.5000	4.5000	4.5000	4.5000

FS	I	J=2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
	13	0.5378	0.5379	0.5387	0.5914											
	12	0.5771	0.5709	0.5517	0.5380	0.6070										
	11	0.6086	0.6081	0.5985	0.5613	0.5411	0.6136									
	10	0.6065	0.6120	0.6174	0.5980	0.5493	0.5407	0.6172								
	9	0.5961	0.6056	0.6212	0.6204	0.5756	0.5437	0.5401	0.6189							
	8	0.5857	0.5978	0.6194	0.6312	0.6061	0.5565	0.5423	0.5400	0.6184						
	7	0.5778	0.5920	0.6166	0.6351	0.6284	0.5899	0.5533	0.5428	0.5404	0.6160					
	6	0.5730	0.5893	0.6146	0.6348	0.6396	0.6250	0.5957	0.5640	0.5459	0.5413	0.6121				
	5	0.5715	0.5895	0.6129	0.6299	0.6379	0.6372	0.6291	0.6135	0.5894	0.5590	0.5418	0.6065			
	4	0.5740	0.5913	0.6086	0.6181	0.6223	0.6238	0.6237	0.6215	0.6150	0.6006	0.5751	0.5417	0.5980		
	3	0.5807	0.5900	0.5967	0.5968	0.5954	0.5949	0.5960	0.5980	0.5992	0.5964	0.5864	0.5657	0.5339	0.5861	
	2	0.5220	0.5489	0.5497	0.5478	0.5474	0.5487	0.5514	0.5552	0.5589	0.5608	0.5587	0.5501	0.5316	0.5226	0.5675
	1	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

TPILE	WA	FSA	FVA	FBA	QHUP	QHDWN	QVUP
56.08520	0.76002	0.58217	0.30691	0.51736	-199706.82812	199822.84375	-151.97047
WSTAR	WLOST	W22	WOUT	ARATE	TAVG	HMIN	SHMIN
4498.64648	4489.67207	-4640.61719	-151.97047	-2.35510	73.59202	0.11930	23.00000
HSTAR	HUSED	H22	HOUT	HSTOR	HOFF	WLOST/WPILE	WLOST/HUSED
4014.44312	4034.00049	-3339.53735	0.11602	674.78973	0.00000	0.22286	12.42955

Table A-5 (continued)

TIME = 360.00 HOURS 15.00 DAYS

TI	I	J=2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
	13	24.1052	23.9671	23.3654	21.2877											
	12	41.5714	40.5769	36.9760	30.3755	21.5378										
	11	54.0194	52.4626	47.5414	39.2535	29.4076	21.2526									
	10	61.4364	59.5699	54.2763	46.0232	36.3887	27.7080	21.0048								
	9	65.8861	63.8235	58.4805	50.7618	42.2319	33.2420	26.6348	20.8964							
	8	68.6328	66.4038	61.1217	54.0898	46.8267	39.5238	32.1438	26.4715	20.9470						
	7	70.3008	67.8919	62.7437	56.5268	50.5884	45.1123	39.1678	32.7326	27.2931	21.1764					
	6	71.1830	68.5869	63.7219	58.5574	54.0880	50.2720	46.4000	41.7798	35.8829	29.3225	21.6344				
	5	71.3922	68.7086	64.4839	60.7745	58.0236	55.8621	53.6861	50.9813	47.2309	41.6862	32.9668	22.6511			
	4	70.9933	68.6152	65.0709	63.8423	62.9024	62.2667	61.4791	60.2630	58.3875	55.4812	50.7046	41.9833	24.2837		
	3	70.3696	69.0221	67.9708	67.9525	68.3008	68.5434	68.4842	68.0631	67.2472	65.9473	63.8836	60.2333	52.1926	25.8099	
	2	70.3039	70.2452	70.6193	71.2604	71.7279	71.9253	71.8755	71.6145	71.1624	70.5050	69.5478	68.0048	65.0536	57.6865	23.3532
	1	4.5000	4.5000	4.5000	4.5000	4.5000	4.5000	4.5000	4.5000	4.5000	4.5000	4.5000	4.5000	4.5000	4.5000	4.5000

FS	I	J=2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
	13	0.5478	0.5478	0.5488	0.6338											
	12	0.6358	0.6283	0.5991	0.5531	0.6617										
	11	0.6762	0.6760	0.6679	0.6150	0.5564	0.6717									
	10	0.6630	0.6712	0.6838	0.6677	0.5841	0.5539	0.6768								
	9	0.6427	0.6570	0.6878	0.6909	0.6361	0.5636	0.5515	0.6790							
	8	0.6254	0.6441	0.6777	0.6996	0.6764	0.6007	0.5587	0.5511	0.6785						
	7	0.6130	0.6354	0.6731	0.7017	0.6998	0.6574	0.5942	0.5604	0.5529	0.6757					
	6	0.6047	0.6318	0.6706	0.6999	0.7092	0.6972	0.6659	0.6193	0.5741	0.5567	0.6710				
	5	0.6037	0.6328	0.6688	0.6930	0.7042	0.7055	0.6998	0.6864	0.6605	0.6138	0.5614	0.6641			
	4	0.6084	0.6365	0.6693	0.6763	0.6812	0.6827	0.6835	0.6836	0.6810	0.6719	0.6472	0.5866	0.6493		
	3	0.6195	0.6352	0.6491	0.6436	0.6398	0.6375	0.6378	0.6403	0.6433	0.6444	0.6412	0.6306	0.5905	0.6264	
	2	0.5220	0.5672	0.5659	0.5614	0.5592	0.5597	0.5624	0.5666	0.5713	0.5754	0.5776	0.5772	0.5718	0.5403	0.5927
	1	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

TPILE	WA	FSA	FVA	FRA	QHUP	QHDWN	QVUP
52.17630	0.70048	0.62512	0.29966	0.50051	-167681.68750	340304.93750	-159.49232
WSTAR	WLOST	W22	WOUT	ARATE	TAVG	HMIN	SHMIN
7018.33154	7019.27246	-7177.82373	-159.49232	-2.03301	69.46680	0.11694	26.00000
HSTAR	HWSFD	H22	HOUT	HSTOR	HOFF	WLOST/WPILE	WLOST/HUSED
5864.56104	5910.69434	-5138.19824	172.62325	553.73969	0.00000	0.34843	12.18588

TIME = 480.00 HOURS 20.00 DAYS

TI	I	J=2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
	13	22.8851	22.8259	22.5259	21.0132											
	12	31.2347	30.9409	29.8921	27.1617	21.1804										
	11	37.5098	36.7683	34.8532	31.6999	26.9465	21.0412									
	10	43.5121	41.8559	38.7944	35.2615	31.1880	26.3670	20.9239								
	9	49.8520	47.1170	42.2738	38.1886	34.4315	30.5203	25.9995	20.8742							
	8	55.2416	51.6854	45.4881	40.6420	37.0890	33.8357	30.2320	25.8732	20.9064						
	7	59.0460	54.9617	48.0196	42.7215	39.4429	36.7317	33.9275	30.5832	26.3817	21.0398					
	6	61.3036	56.8699	49.8561	44.7822	41.9291	39.7992	37.6463	35.0998	31.8460	27.4326	21.3227				
	5	62.1935	57.6749	51.4613	47.5480	45.5433	44.1430	42.6659	40.7789	38.2158	34.6759	29.6178	21.8417			
	4	61.9450	58.1056	54.0196	52.4066	52.1058	51.9420	51.3661	50.1403	48.0939	44.9892	40.3966	33.5816	22.7942		
	3	61.4939	59.7166	58.9769	59.9245	61.1271	61.8886	62.0331	61.5445	60.4019	58.4822	55.4091	50.2521	40.9188	23.8365	
	2	62.8375	63.6357	65.2651	66.9316	68.0208	68.5349	68.5910	68.2738	67.6136	66.5669	64.9442	62.2162	56.9302	44.8605	22.1592
	1	4.5000	4.5000	4.5000	4.5000	4.5000	4.5000	4.5000	4.5000	4.5000	4.5000	4.5000	4.5000	4.5000	4.5000	4.5000

Table A-5 (continued)

FS	I	J=2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
	13	0.5571	0.5571	0.5583	0.6790											
	12	0.6522	0.6432	0.6104	0.5612	0.7207										
	11	0.7098	0.7072	0.6970	0.6304	0.5664	0.7363									
	10	0.7132	0.7182	0.7205	0.6926	0.5983	0.5639	0.7445								
	9	0.7015	0.7145	0.7300	0.7241	0.6575	0.5761	0.5613	0.7481							
	8	0.6844	0.7054	0.7321	0.7396	0.7047	0.6192	0.5708	0.5610	0.7474						
	7	0.6684	0.6969	0.7318	0.7475	0.7345	0.6841	0.6128	0.5731	0.5632	0.7432					
	6	0.6575	0.6928	0.7322	0.7515	0.7510	0.7324	0.6956	0.6422	0.5895	0.5683	0.7366				
	5	0.6540	0.6944	0.7334	0.7512	0.7554	0.7520	0.7425	0.7249	0.6930	0.6372	0.5750	0.7275			
	4	0.6607	0.7001	0.7305	0.7398	0.7408	0.7399	0.7389	0.7273	0.7325	0.7194	0.6856	0.6065	0.7078		
	3	0.6759	0.6990	0.7086	0.7023	0.6943	0.6892	0.6880	0.6901	0.6936	0.6962	0.6981	0.6832	0.6234	0.6743	
	2	0.5220	0.6030	0.5946	0.5842	0.5786	0.5774	0.5794	0.5837	0.5894	0.5954	0.6011	0.6062	0.6071	0.5652	0.6206
	1	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

TPILE	WA	FSA	FVA	FBA	QHUP	QHDWN	QVUP
44.07898	0.65854	0.66024	0.29469	0.48848	-155639.37500	478424.81250	-160.14142
WSTAR	WLOST	W22	WOUT	ARATE	TAVG	HMIN	SHMIN
8802.13281	8803.52930	-8962.27441	-160.14142	-1.80253	57.14380	0.11462	55.00000
HSTAR	HUSED	H22	HOUT	HSTOR	HOFF	WLOST/WPILE	WLOST/HUSED
7111.03320	7173.92676	-6423.52979	319.78543	367.71786	0.00000	0.43699	12.02914

TIME = 600.00 HOURS 25.00 DAYS

TI	I	J=2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
	13	22.7715	22.7252	22.4590	21.0134											
	12	30.6132	30.4297	29.6085	27.0986	21.2005										
	11	35.9578	35.5480	34.2041	31.5018	26.9945	21.0812									
	10	39.9177	39.2693	37.5711	34.8597	31.2025	26.5125	20.9768								
	9	43.3341	42.2139	40.1842	37.5159	34.3740	30.6991	26.1950	20.9311							
	8	46.7053	44.9610	42.7980	39.6716	36.9311	33.9810	30.4618	26.1607	20.9561						
	7	49.6730	47.2917	44.8087	41.4798	39.1305	36.7391	34.0378	30.7077	26.4718	21.0607					
	6	51.8865	48.9944	45.4392	41.1500	41.2703	39.4150	37.3303	34.7975	31.5638	27.2116	21.2579				
	5	53.1267	50.0706	46.8485	45.1145	43.8987	42.6740	41.1735	39.2212	36.6526	33.2230	28.4986	21.5329			
	4	53.4780	51.0073	49.0307	48.4414	48.2081	47.7582	46.8288	45.3175	43.1514	40.0928	35.8442	29.9904	21.7616		
	3	53.9625	53.2880	53.7071	54.9574	56.0148	56.4495	56.1156	54.9394	52.8010	49.4458	44.5246	38.0181	30.2827	21.6086	
	2	56.7764	58.4710	60.9464	62.9924	64.1859	64.5937	64.3157	63.3554	61.5588	58.4943	53.2164	44.4118	33.9017	26.3360	20.5908
	1	4.5000	4.5000	4.5000	4.5000	4.5000	4.5000	4.5000	4.5000	4.5000	4.5000	4.5000	4.5000	4.5000	4.5000	4.5000

FS	I	J=2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
	13	0.5662	0.5663	0.5677	0.7296											
	12	0.6617	0.6522	0.6177	0.5674	0.7882										
	11	0.7233	0.7202	0.7097	0.6402	0.5744	0.8115									
	10	0.7302	0.7345	0.7395	0.7060	0.6085	0.5726	0.8242								
	9	0.7279	0.7373	0.7481	0.7403	0.6706	0.5862	0.5701	0.8298							
	8	0.7226	0.7379	0.7543	0.7582	0.7206	0.6313	0.5809	0.5699	0.8288						
	7	0.7152	0.7374	0.7589	0.7684	0.7529	0.6996	0.6251	0.5835	0.5724	0.8223					
	6	0.7084	0.7383	0.7640	0.7751	0.7722	0.7518	0.7127	0.6565	0.6010	0.5779	0.8121				
	5	0.7062	0.7430	0.7704	0.7800	0.7813	0.7766	0.7659	0.7465	0.7118	0.6519	0.5853	0.7988			
	4	0.7139	0.7520	0.7783	0.7793	0.7782	0.7762	0.7739	0.7702	0.7623	0.7451	0.7056	0.6185	0.7722		
	3	0.7302	0.7560	0.7611	0.7518	0.7427	0.7369	0.7351	0.7363	0.7387	0.7392	0.7332	0.7108	0.6358	0.7272	
	2	0.5220	0.6428	0.6264	0.6118	0.6036	0.6012	0.6031	0.6084	0.6160	0.6251	0.6339	0.6373	0.6259	0.5690	0.6527
	1	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

TPILE	WA	FSA	FVA	FBA	QHUP	QHDWN	QVUP
40.30994	0.63091	0.68570	0.29113	0.47962	-169867.46875	594943.68750	-160.23677
WSTAR	WLOST	W22	WOUT	ARATE	TAVG	HMIN	SHMIN
9974.15137	9976.06445	-10134.38770	-160.23677	-1.65202	48.18914	0.11235	73.00000
HSTAR	HUSED	H22	HOUT	HSTOR	HOFF	WLOST/WPILE	WLOST/HUSED
7999.61768	8067.51465	-7291.70557	425.07623	282.83569	0.00000	0.49520	11.91795

Table A-5 (continued)

TIME = 720.00 HOURS 30.00 DAYS

TI	I	J=2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
	13	22.7491	22.7043	22.4453	21.0282											
	12	30.7562	30.5772	29.7589	27.2417	21.2392										
	11	36.1553	35.7703	34.4582	31.7628	27.1972	21.1294									
	10	40.0291	39.4760	37.8763	35.2067	31.5266	26.7388	21.0290								
	9	42.9582	42.2427	40.4763	37.9154	34.7931	31.0487	26.4249	20.9832							
	8	45.5524	44.4235	42.4998	40.0877	37.3877	34.4008	30.7976	26.3715	21.0016						
	7	47.7388	46.2399	44.0944	41.8722	39.5761	37.1488	34.3741	30.9500	26.6064	21.0835					
	6	49.3781	47.5814	45.3611	43.4264	41.5657	39.6313	37.4418	34.8059	31.4893	27.1018	21.2156				
	5	50.3547	48.4590	46.4764	45.0026	43.6602	42.2200	40.5018	38.3624	35.6670	32.2339	27.7243	21.3454			
	4	50.6941	49.1385	47.8578	47.1014	46.3836	45.4147	44.0198	42.1059	39.6342	36.5479	32.7259	27.9004	21.3782		
	3	51.0015	50.4883	50.5028	50.8209	50.8150	50.1386	48.6225	46.2486	43.2535	39.7515	35.9248	31.7763	26.9617	21.1660	
	2	52.9175	54.0763	55.8082	57.1054	57.4540	56.6689	54.5830	50.9749	45.8283	39.9377	34.9042	31.0358	27.3396	23.6697	20.3702
	1	4.5000	4.5000	4.5000	4.5000	4.5000	4.5000	4.5000	4.5000	4.5000	4.5000	4.5000	4.5000	4.5000	4.5000	4.5000

FS	I	J=2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
	13	0.5757	0.5758	0.5775	0.7877											
	12	0.6708	0.6606	0.6246	0.5733	0.8684										
	11	0.7356	0.7322	0.7148	0.6496	0.5823	0.9023									
	10	0.7439	0.7483	0.7493	0.7189	0.6185	0.5812	0.9213								
	9	0.7435	0.7526	0.7637	0.7557	0.6835	0.5961	0.5790	0.9298							
	8	0.7435	0.7565	0.7716	0.7755	0.7362	0.6434	0.5910	0.5788	0.9282						
	7	0.7414	0.7603	0.7780	0.7872	0.7707	0.7148	0.6372	0.5938	0.5813	0.9181					
	6	0.7387	0.7645	0.7851	0.7956	0.7921	0.7703	0.7291	0.6701	0.6119	0.5869	0.9024				
	5	0.7387	0.7715	0.7942	0.8031	0.8041	0.7987	0.7869	0.7657	0.7284	0.6647	0.5942	0.8817			
	4	0.7479	0.7835	0.8040	0.8070	0.8055	0.8031	0.7998	0.7946	0.7846	0.7642	0.7200	0.6271	0.8436		
	3	0.7649	0.7935	0.7975	0.7888	0.7806	0.7752	0.7727	0.7716	0.7696	0.7641	0.7511	0.7225	0.6416	0.7826	
	2	0.5220	0.6703	0.6527	0.6395	0.6326	0.6317	0.6353	0.6417	0.6479	0.6510	0.6494	0.6432	0.6277	0.5693	0.6863
	1	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

TPILE	WA	FSA	FVA	FBA	QHUP	QHDWN	QVUP
37.87180	0.61013	0.70630	0.28836	0.47257	-189448.54687	694423.37500	-155.47701
WSTAR	WLOST	W22	WOUT	ARATE	TAVG	WMIN	SWMIN
10854.94141	10857.35645	-11010.41797	-155.47701	-1.53946	46.64561	0.11013	86.00000
HSTAR	HUSED	H22	HOUT	HSTOR	HOFF	WLOST/WPILE	WLOST/HUSED
8689.11914	8756.81641	-7954.85937	504.97485	229.28505	0.00000	0.53894	11.84087